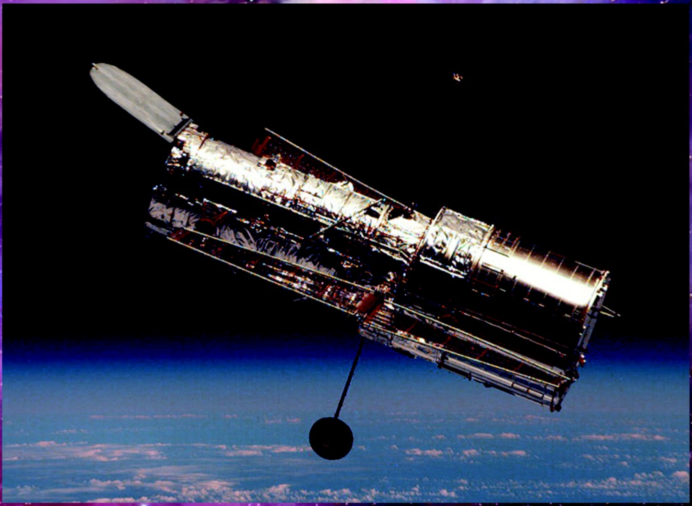
Tools of Astronomy

How they transformed our view of the Universe



Biman Basu

VIGYAN PRASAR

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by Biman Basu

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Foreword

Of late, Vigyan Prasar has emerged as an important resource-cum-facility centre in the field of science communication. In addition to its regular programmes, Vigyan Prasar has undertaken special programmes and national campaigns built around celestial events like Total Solar Eclipse (1995, 1999) and Venus Transit (2004). Software developed on such occasions is extensively utilised by agencies involved in science communication across the country.

The year 2009 has been declared as the International Year of Astronomy (IYA-2009) coinciding with the 400th anniversary of the first astronomical observations with a telescope by Galileo Galilei and the publication of Johannes Kepler's *Astronomia nova* (*New Astronomy*). The central theme of the IYA-2009 is "The Universe Yours to Discover." It is important that all human beings realise the impact of astronomy and basic sciences on our daily lives, and understand how scientific knowledge can contribute to a more equitable and peaceful society.

The IYA-2009 aims at helping people realise how astronomy has enriched almost every human culture and rediscover their place in the Universe through the day and night time sky, and thereby engage a personal sense of wonder and discovery. This will also serve as platform for making the general public aware about the recent astronomical discoveries and stimulate interest in astronomy. Throughout the year, activities would take place in each participating country at different levels.

Based on its past experience, Vigyan Prasar has initiated programmes with activities built around IYA-2009. The activities include production of a 52-episode radio serial in 19 Indian languages including English to be broadcast from 117 stations of All India Radio, a 26-episode television serial on astronomy, development of a variety of software including books, interactive CD-ROMs, and power-point presentations to be used as resource material during training programmes at different levels. An important part of the campaign would be the activities built around the total solar eclipse of 22 July 2009, which would be visible from some parts of India.

It is hoped the present series of publications brought out during IYA-2009 would be welcomed by science communicators, science clubs, resource persons, and individuals; and inspire them to discover the universe and realize their position in it.

Vinay B Kamble
Director
Vigyan Prasar

Preface

Human curiosity about the Sun, Moon and the stars is perhaps as old as the appearance of modern humans on this planet. As the early humans were evolving, their well-developed brain and an erect posture must have made them look up and wonder at the sky and the various phenomena going on there. By about 5000 BC, agriculture was well established and food production had reached a level that freed significant time and effort of early humans for pursuits beyond those needed for survival alone. Out of these developments evolved the first true civilisations – societies with the means and the wish to pursue intellectual, artistic and other creative activities. Among the earliest civilisations was the Sumerian civilisation that flourished around 3500 BC in Babylon, Mesopotamia – the land between the rivers Tigris and Euphrates, which is part of modern-day Iraq. There were others, including those in Egypt, around 3000 BC; in the Indus Valley in India, around 2500 BC; the Minoan civilisation in Crete, around 2000 BC; in China, around 1500 BC; and in Central America (the forerunners of the Incas and the Aztecs), around 1000 BC.

Many of the intellectual activities pursued in the early civilisations arose out of the innate curiosity of the human race in the natural world and one of them was the goings-on in the sky. The daily movement of the Sun across the sky from east to west, the changing phases of the Moon, and the sparkling star-speckled night skies must have appealed to the first sky watchers as it does to us even today. But unlike modern humans, the early humans did not have the means to study the celestial phenomena except with unaided eye. Their vision of the Earth, the sky and the Universe was based solely on visual observations and their fertile imagination.

Yet, some of the ancient civilisations and prehistoric stone-age cultures had a surprisingly good understanding of the motions of the celestial bodies and of practical geometry. Around 3100 BC stone-age people in what is now United Kingdom had built one of the earliest astronomical observatories, in the shape of concentric circles of large standing stones. This group of standing stones at Stonehenge was probably used for marking the directions of sunrise, sunset, moonrise and moonset at different times of the year.

About the same time as Stonehenge was being built, much more advanced civilisations were flourishing in India, China, Egypt and Babylon. Each had its own system of astronomy, inextricably mixed with astrology, mythology and religion. These ancient civilisations used their knowledge of the motions of the celestial bodies to make calendars and predict regular celestial events for organising various religious rituals. They also developed considerable skill in using the stars for finding directions and, consequently, for navigation at sea.

But assessing the position of the Sun, Moon or the stars in the sky merely by looking at them with unaided eye is not a reliable method. It is not easy to tell when the Sun is exactly on the meridian, or when a star is transiting across the meridian, simply by looking at them. Some tools were needed to do it in a methodical way with some accuracy.

Before the telescope was invented, a host of simple but ingenious instruments were designed and built by astronomers around the world. With the help of these simple tools some of them were able gather enormous amounts of data about the positions and movements of the celestial bodies that helped them compute orbits of planets, corroborating the Copernican heliocentric model of the solar system and also to predict eclipses.

After invention of the telescope in early 17th century and its use for sky observation by the Italian astronomer Galileo Galilei, the study of astronomy underwent sea change. The telescope opened up an entirely new vista of the sky. Galileo found the surface of the Moon to be pockmarked with craters rather than smooth, as it appears to the unaided eye. He was surprised to find the profusion stars when he turned his instrument towards the Pleiades cluster and the Milky Way. In Pleiades, he found as many as forty stars compared to only six or seven visible with the naked eye. The Milky Way turned out to be a conglomeration of multitude of stars. He also discovered that Venus shows phases like the Moon. But his most momentous discovery was that of the four moons of Jupiter, which he had erroneously believed to be new planets, as he mistook Saturn's rings to be.

What Galileo started with his refracting telescope soon became a revolution in astronomy. Larger and larger refractors came up and new observatories were set up to carry out astronomical studies. Reflecting telescopes became more popular and widely used because of they could be built larger and more powerful than refractors. The advent of photography, spectroscopy and other techniques helped in enlarging the scope of astronomy from being merely an observational science to a full-fledged scientific discipline. Techniques to measure stellar distances pushed the limits of the visible Universe to thousands of millions of light years. Our Sun turned out to be an insignificant star among thousands of millions that made up our Milky Way galaxy.

After the coming of the Space Age, the limitations of ground-based observation in optical wavelengths because of the turbulence of Earth's atmosphere were overcome by placing a telescope in Earth orbit. At the same time, advancements in imaging technology, such as adaptive optics and speckle imaging helped in vastly improving the quality of images produced by ground-based telescopes that led to the discovery of planets around far away stars.

Technological developments during the Second World War led to yet another breakthrough – the discovery of radio waves coming from space – that opened up a new dimension in our understanding of the Universe. Galaxies and stars, and even our Sun, which appeared serene and shining steadily, turned out to be objects seething with extreme violence, spewing out highly energetic particles and powerful radiation. The Universe as seen through the radio telescope appeared totally different from the visible Universe we are familiar with.

Radio telescopes also brought forth new kinds of star-like objects such as pulsars and quasars the existence of which were never known before. Pulsars turned out to be fast spinning dead stars that behaved like extremely accurate celestial clocks, sending out precisely timed pulses of radio waves. Quasars on the other hand are extremely distant objects, which emit extremely powerful radio waves. The real nature of quasars and the source of its enormous energy still remain a mystery, although it is believed that black holes at the centre of galaxies could be responsible.

Space-borne telescopes also revealed the cosmos in wavelengths never seen before. Space telescopes working in infrared, ultraviolet, X-ray and gamma-ray wavelengths brought out extremely violent processes going on in the far reaches of the cosmos.

Astronomers today have a plethora of tools to explore the Universe thanks to advancements in optics, electronics, space technology, and radio communication. These tools have made possible not only the exploration of all the planets of our solar system and their moons, but also enabled astronomers to explore distant galaxies and peep into the heart of our Milky Way galaxy. We now know that our Universe is an extremely violent place. If not in the vicinity of our solar system, violent activity goes on almost everywhere in the cosmos where massive stars explode in their death throes with the brilliance of a thousand Suns, or binaries collide, spewing forth deadly gamma rays. This book is an attempt to present the story of the remarkable astronomical tools that have led to the astounding discoveries in astronomy and made possible our present understanding of the cosmos.

1

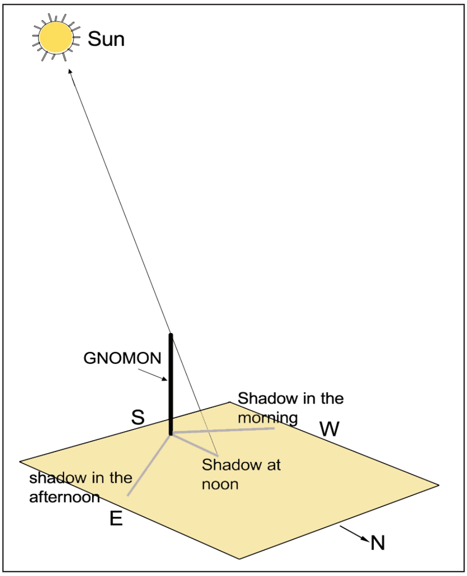
Wood, metal and masonry

Early astronomers were mostly concerned with determining the location of objects on the celestial sphere, as seen on a particular date, at a particular time and a particular location on Earth. This is one of the oldest branches of astronomy called positional astronomy, which played a crucial role in the making of calendars and determining auspicious times for religious ceremonies.

To determine the position of the celestial objects in the sky as accurately as possible, early astronomers had devised ingenious tools that enabled them to compile useful catalogues of stars and planetary tables that were surprisingly accurate for their time. Using these tools they mapped the stars and made tables to predict the future positions of the Sun, Moon, and planets. This knowledge was important, for the sky served as a clock, a calendar, and a navigational aid to help seafarers find their way, although anomalies were discovered later in the predicted and actual position of planets that ultimately led to the establishment of the heliocentric model of Nicolaus Copernicus and the laws of planetary motion by Johannes Kepler.

The gnomon

One of the earliest and simplest tools used for astronomical observations was the gnomon. The gnomon is one of the first scientific instruments ever made, originating with the Chaldean astronomers of Babylon and from there brought



A gnomon. The gnomon can be used for finding the declination of the Sun through the year, by measuring its shadow at noon.

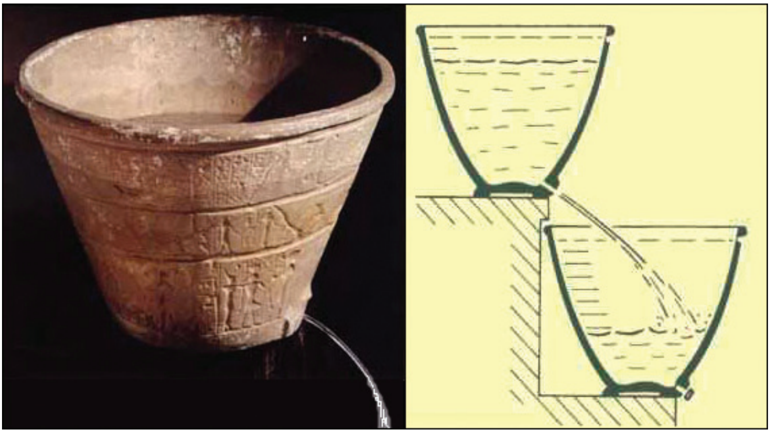
to the Greek world. The simplest gnomon consists of a straight vertical rod made of wood, metal, or ivory, fixed to a horizontal base and is based on the same principle as the modern sundial. The gnomon is mentioned in the ancient Indian text *Atharvaveda* and some of the *Brahmânas*. The Sulba-sutras mention the use of the gnomon for the determination of cardinal points. Varâhamihira in his *Pañcasiddhântikâ* gives details of the use of the gnomon in astronomy.

The gnomon can be used for finding the declination of the Sun through the year, by measuring its shadow at noon. In the early morning, its shadow is long and points roughly westward; as the day progresses, the shadow shortens and rotates until, at noon, it is the shortest and points exactly due north. From the height of the gnomon and the length of its shadow at noon, the solar altitude can be worked out using a little trigonometry. The declination of the Sun (its angle north or south of the celestial equator) is given by the sum of the solar altitude at noon and the local latitude, minus 90°. [From Delhi, for example, if the solar altitude at noon is 45°, then the declination of the Sun would be 45° + 28°40′ (latitude of Delhi) -90°; that is, -16°6′.] After noon, the shadow of the gnomon becomes longer and longer and rotates until, in the late afternoon, it points roughly eastward.

The water clock or clepsydra

Measurement of time constituted an important part of early astronomical studies, as it is today, and several types of time-measuring devices were designed. One of the earliest timekeepers used was the water clock or clepsydra (Greek *kleptein*, to steal; *hydro*, water), which was operated by means of a regulated flow of liquid into (inflow type) or out from (outflow type) a vessel where the amount was then measured. Water clocks, along with sundials, were probably the oldest time-measuring instruments. Given their great antiquity, where and when they first existed is not known.

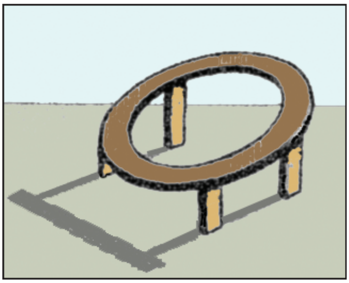
The bowl-shaped outflow device is the simplest form of a water clock and is known to have existed in Babylon and in Egypt around 16th century BC. Other regions of the world, including India and China, also have early evidence of water



Egyptian clepsydra. The bowl-shaped outflow device is known to have existed around 16th century BC.

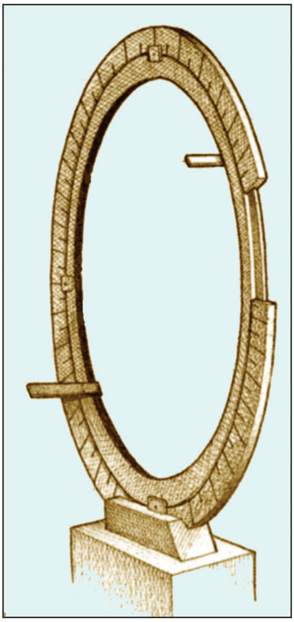
clocks, but the earliest dates are less certain. The use of water clocks is referred to in the Indian text *Vedânga Jyotisa*, which dates back to 400 BC. The earliest type probably consisted of a simple vessel having a small orifice at its bottom, which permitted water to flow out in a fixed unit of time. In course of time, the water-flowing type gave place to the sinking type in which a metal vessel with a hole was allowed to sink in a larger vessel containing water. A more developed form of the clepsydra is described in the *Sûrya-siddhânta*, an Indian astronomical text written around AD 600. This water clock consisted of a 'hemispherical copper vessel, with a hole in the bottom, set in a basin of pure water, sinking sixty times in a day and night'. Of course, such simple water clocks were not very accurate, but they must have served a useful purpose in their time.

Armillaries



Equinoctial armillary was a simple bronze ring that was set up horizontally.

An armilla is a bracelet, a metal ring several centimetres in diameter. It was one of the most ancient of astronomical instruments. Two astronomical instruments were based on the armilla – the equinoctial armillary and the solstitial armillary. The equinoctial armillary was a simple bronze ring that was set up horizontally so that the plane of the ring was parallel to the plane of the Earth's equator. With this setting, twice a year – once in the spring and once in the autumn – on the day of the equinoxes, the shadow of the upper half of the ring would fall precisely on the lower half; that is, the shadow of the ring would be a straight line rather than an ellipse. So this simple device could be used to mark the equinoxes.

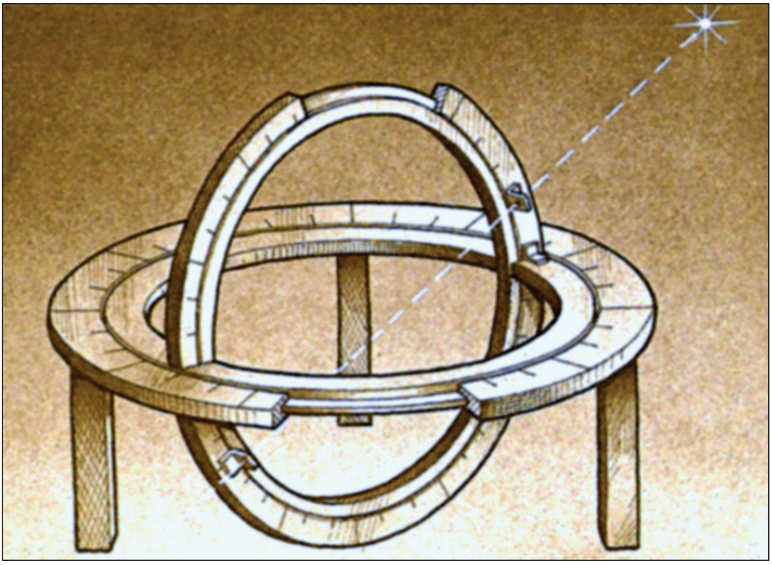


The solstitial armillary.

In the solstitial armillary, two bronze rings are used – one sliding within the other. The pair of bronze rings are set vertically on a stone pillar and aligned so that the plane of the rings point precisely north and south. The inner ring is movable and has two pins on opposite sides, which serve as sights. Readings are made by moving the inner ring until the shadow of the upper pin falls exactly on the lower pin. The angle is read off from the fixed scale on the outer ring. The device was primarily designed for determining the meridian altitude of the Sun at noon.

Although better than the gnomon for determining the meridian altitude of the Sun at noon, the solstitial armillary had one major limitation; it was designed to measure the altitude of the Sun at noon only. But astronomical phenomena are not always confined to the meridian, and an astronomer determining a star's position needs two measurements to fix its location in the sky. To do that the armillary sphere was invented, by combining two solstitial armillaries and replacing the two pins by a pair of sights along which a star could be looked at.

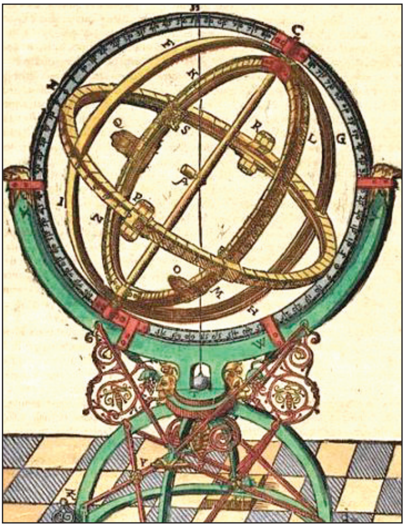
In the armillary sphere, the two pairs of rings are set at right angles and mounted so that one of the rings is parallel to the plane of the equator. To use the armillary sphere, the



The armillary sphere uses two pairs of rings set at right angles and mounted so that one of the rings is parallel to the plane of the equator. The innermost vertical ring, with the sights on it, is moved so that the star or planet of interest can be seen.

innermost vertical ring, with the sights on it, is moved so that the star or planet of interest can be seen. From the readings on two scales marked on the outer of the two rings the position of the star or planet in terms of declination (the astronomical equivalent of latitude) and right ascension (the astronomical equivalent of longitude) of the star or planet can be determined. With instruments such as these astronomers as early as 290 BC could compile reasonable accurate catalogue of star positions.

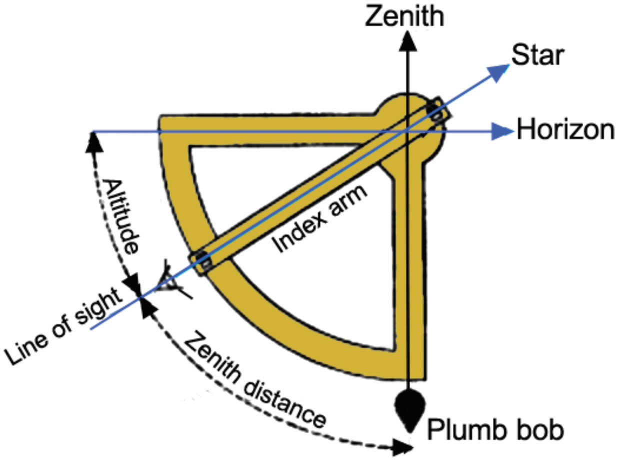
More complex armillary spheres had several rings made of wood or metal, representing the great circles of the celestial sphere. More elaborate instruments also had rings representing the horizon, meridian, equator, tropics, polar circles, and an ecliptic hoop. The sphere represented a skeleton of the celestial globe, with circles divided into degrees for angular measurement. By moving the armillary rings, one could demonstrate how the stars moved. While, early models had the Earth at the centre of the Universe, in later models the Sun was placed at the centre. These armillary spheres were mostly used as teaching aids.


Armillary sphere of Tycho Brahe had several rings made of wood or metal, representing the great circles of the celestial sphere.

The exact origin of the armillary sphere is not known. Some sources credit Greek philosopher Anaximander of Miletus (611-547 BC) with inventing the armillary sphere, others credit Greek astronomer Hipparchus (190 - 120 BC). Armillary spheres first appeared in China during the Han Dynasty (206 BC - AD 220). In India, the armillary sphere finds mention as the '*gola yantra*' in the *Sûrya-siddhânta*, the *Siddhânta-siromani*, and other astronomical texts. Armillary spheres became widespread and increased in sophistication during the Middle Ages (c. AD 1100-1453).

The quadrant

Another simple instrument used by early astronomers for determining the position of stars and planets in the night sky was the quadrant. An astronomical quadrant is essentially a graduated quarter of a circle, set up to measure the altitude of astronomical objects above the horizon. The graduations from 0-90° are marked on the circumference, or



The simple quadrant could be used to determine meridian altitudes of stars and planets as they crossed the observer's meridian.

limb of the instrument, over which usually a sight or index arm moves. Astronomical quadrants were used mainly for determining the altitude of a celestial body above the horizon, but it could be used for many other purposes. Meridian altitudes of the Sun or a bright star could be employed for determining the geographical latitude of an observer; or, at known latitude, the observer could obtain the time from the measured altitude.

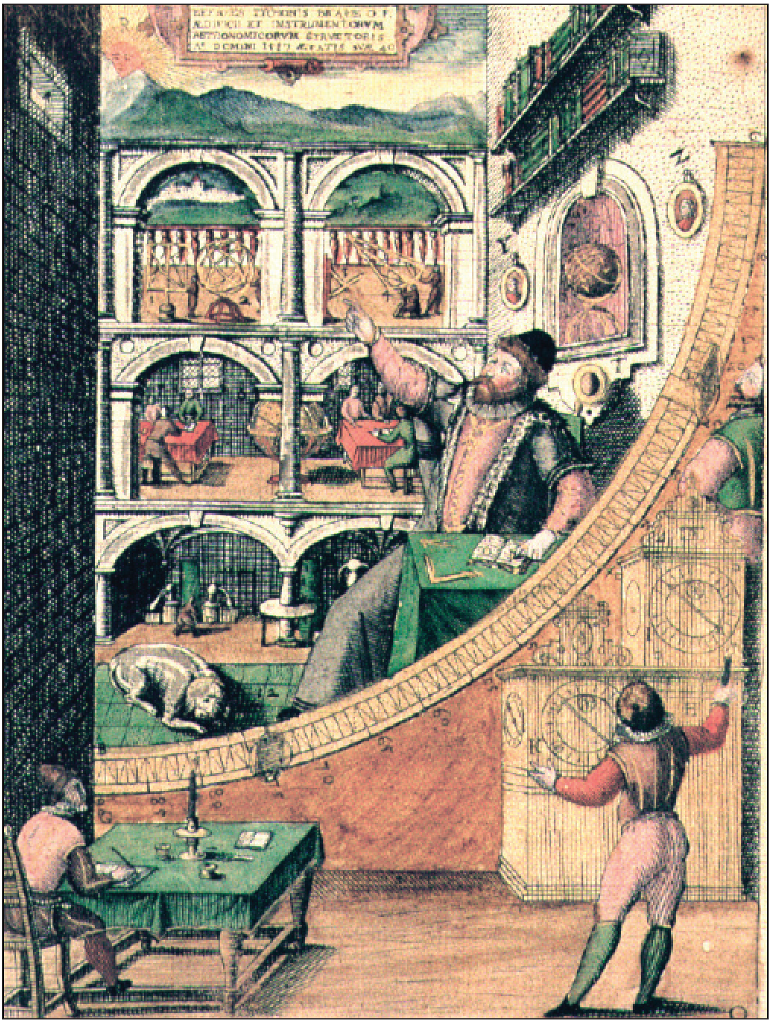
As it was originally used, the plane of the quadrant was adjusted to lie in the plane of the meridian. Vertical alignment was indicated by a plumb-bob suspended from the quadrant's centre. Pivoted from this centre was one end of a movable rod approximately equal in length to the radius of the quadrant. Sights mounted on the rod enabled observations to be made of stars and planets as they crossed the observer's meridian, and an angular scale inscribed on the periphery of the quadrant gave their meridian altitudes.

Tycho's instruments

Tycho Brahe.

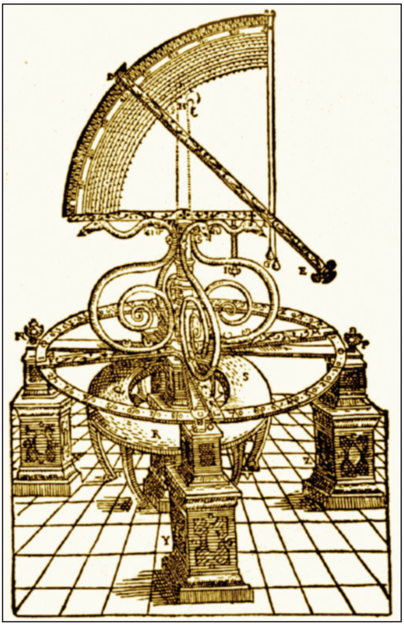
Danish astronomer Tycho Brahe was a master at constructing astronomical instruments. He lived before the telescope and binoculars were invented, and made his observations solely with the naked eye and with the help of his ingenious sighting devices. His instruments were unique. The world had never before seen so many or such good and reliable astronomical instruments. Precision, stability and permanency were significant for all of them. The instruments were firmly erected in observatories specially designed for their purpose. It is said that, while earlier astronomers had to calculate with errors of up to ten minutes of arc in their observations, Tycho's observations were mostly good to within half a minute of arc. He also took long series of observations with the same permanent instruments, which have been greatly appreciated by later astronomers.

Tycho built several quadrants for his astronomical observations. Quadrants came in two forms: mural quadrants, which were fixed to a meridian wall and used to measure meridian altitudes; and altazimuth quadrants, which could be rotated to any bearing for the simultaneous determination of the altitude and the azimuth of a celestial body. Mural quadrants were considered the most accurate because they were not only large, but also did not have any wear and tear due to movement. But mural quadrants could be used only for making observations restricted to the meridian. One of the largest mural quadrants was completed in the 1582 by Tycho at his observatory Uraniborg on the isle of Hven.



Tycho Brahe and his great mural quadrant at Uraniborg on the Isle of Hven. Completed in 1582, the accuracy of this instrument, based on comparison with eight reference stars, has been estimated to 34.6 seconds of arc.

Altazimuth quadrants were much smaller in size. Built of wood or metal, many of these quadrants were designed to rotate about a vertical axis. Tycho built several of these instruments. His smallest quadrant, built in 1573, had a radius of about 39 cm and was made of gilt brass. The instrument was used for determining altitudes. Hand-held versions of the altazimuth quadrant were very popular in the Middle Ages for determining the time from the Sun's altitude.

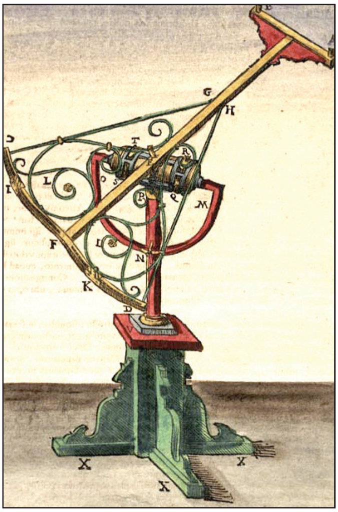


Tycho's azimuthal quadrant.

Tycho's naked-eye observations formed the basis of the first new star catalogue since antiquity. His most significant contribution to the history of science was the accuracy of his astronomical observations. It was on the foundations of Tycho's observations that the German astronomer, mathematician Johannes Kepler discovered his laws of planetary motion. Though Tycho did not believe the Earth moved around the Sun, his work provided support for the heliocentric system, proposed by the Polish astronomer Nicolaus Copernicus in 1543. Mathematically, Copernicus's and Tycho's models are equivalent, but Tycho believed that the Universe is Earth-centred, and devised a model in which the five visible planets – Mercury Venus, Mars, Jupiter, and Saturn – revolve around the Sun, but the Sun continues to revolve around the fixed point of the Earth.

Tycho himself described his astronomical instruments in his book *Astronomiæ Instauratæ Mechanica* ('Instruments for the Restoration of Astronomy'), published in 1598. The book describes more than 20 of his astronomical inventions, especially the instruments through which the stars and planets could be observed and by which angular separations and ascensions could be measured. Tycho's astronomical sextants are famous for the accuracy they provided. They could achieve a precision of up to 80 seconds of arc.

Tycho's revolving azimuth quadrant, which he built in 1586, was made partly of steel, partly of brass. The radius was 155 cm. It had an azimuth circle, 230 cm in diameter, mounted directly on the wall. Both altitudes and azimuths could be taken. It had a scale with the minutes divided into four parts, which allowed readings to an accuracy of fifteen seconds of arc. The instrument could be turned all around the horizon. With this instrument, using the Polaris as reference, Tycho could determine the latitude of his observatory with great accuracy. He measured the highest and lowest altitude of the star and from several observations he calculated a mean figure. His calculated latitude differed from the correct one by only 14 seconds of arc!



Tycho's bipartite arc was designed for measuring small angular distances between celestial objects.

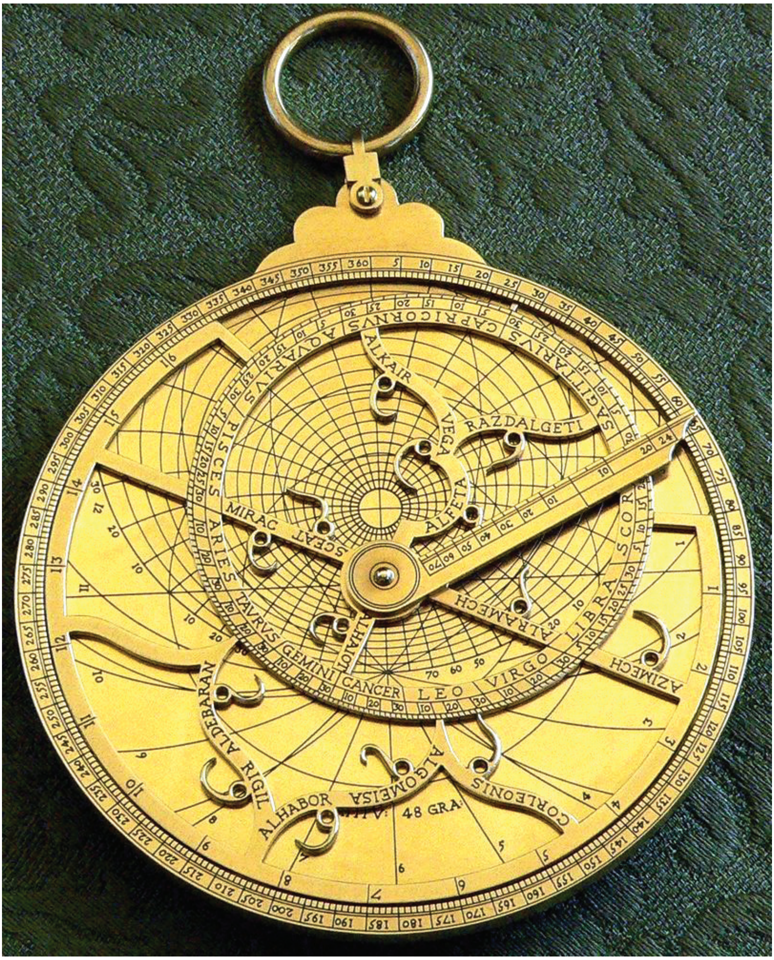
Tycho designed several instruments for measuring small angles. The bipartite arc was one of them. It consisted of two arcs of brass, each covering 30°. They were mounted on the end of a 155-cm long bar of iron with two small cylinders as aiming points in the opposite end. The instrument was handled by two observers. Using this instrument, star positions could be measured up to an accuracy of 30 seconds of arc, or half the visual resolution limit of the naked-human eye at 60 seconds of arc. With this instrument Tycho later checked all the distances between the stars in the constellation of Cassiopeia.

With his mural quadrant and other naked-eye instruments, Tycho recorded the positions of hundreds of stars and followed the motions of planets over decades. His mass of data was invaluable for later astronomers. Tycho's measurements were the most accurate ever made until telescopes came on the scene.

The astrolabe

Another widely used astronomical instrument of the pre-telescope era was the astrolabe, which was mostly made of brass. Part observing tool and part calculator, it was used from ancient times up until the 17th century, when the invention of the telescope displaced it as the premier tool of astronomers. In the 15th and 16th centuries, the astrolabe was a basic astronomical education tool in Europe. Knowledge of astronomy was fundamental, and skilled astrolabe use was a sign of proper upbringing and education. In its day, it was the most accurate astronomical device available. And an extremely versatile tool, with as many as 1,000 different functions.

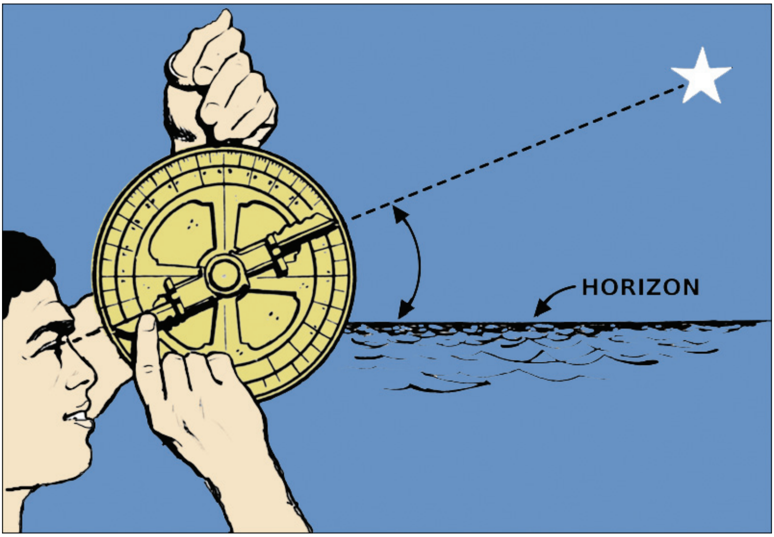
The astrolabe is, in essence, a two-dimensional model of the celestial sphere in relation to the Earth, based on the assumption that the Earth is at the centre of the Universe. This hand-held device had a moveable arm to measure the angle of a bright star above the horizon – the star's 'altitude'. Rotating a metal map of stars to match engraved curves, the



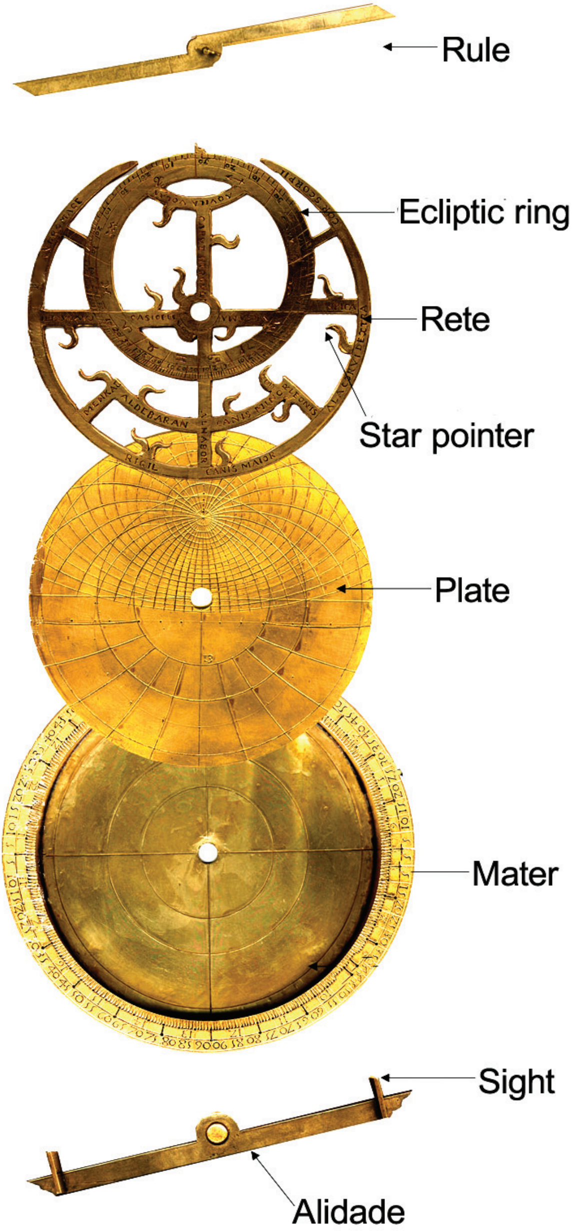
The astrolabe was part observing tool and part calculator and was an extremely versatile tool, with as many as 1,000 different functions.

user could determine time and direction, locate stars in the sky, determine when the Sun would rise or set, and make other calculations. The astrolabe is in fact a multifunctional instrument and can be used to tell the time, to determine the length of day and night, to simulate the movements of the heavenly bodies, as well as for surveying. Three types of astrolabe are known – the spherical, the flat, and the rod. But the flat type, also known as the planispheric type, is the most popular. The planispheric astrolabe enabled astronomers to calculate the position of the Sun and prominent stars with respect to both the horizon and the meridian. It provided them with a plane image of the celestial sphere and the principal circles – namely, those representing the ecliptic, celestial equator, and tropics of Cancer and Capricorn. Because of such features, the planispheric astrolabe can be regarded as a kind of rudimentary analogue computer.

The origins of the astrolabe are shrouded in mystery, but the underlying theory for its construction, the stereographic projection, probably date back to 225 BC, although it has also been attributed to Hipparchus (2nd century BC). Although known to the Greeks, this versatile instrument was perfected by the Islamic astronomers in West Asia, Central Asia and Spain and travelled to India along



Use of astrolabe to determine position of stars.



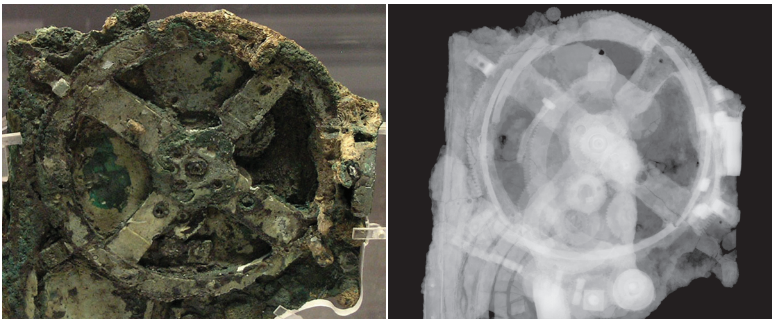
Parts of an astrolabe.

with Arab astronomy. The earliest surviving astrolabe is an Islamic instrument dated AD 927-928.

The basic design of the astrolabe has not changed throughout the centuries, although many features were added for different purposes. The typical planispheric astrolabe employed by mediaeval astronomers measured from 8 to 46 cm and was made of metal – usually brass or iron. A typical astrolabe consists of several layers. The base is a hollow disk, called the mater (mother), which is deep enough to hold one or more flat plates called climates. (Most astrolabes had one or more climates engraved with coordinate lines for different latitudes.) The rim of the mater is typically graduated into hours of time, or degrees of arc, or both. Above the mater and tympan, is an open-pattern disk (the rete) with a 'map' of the stars that rotates on the mater around a centre pin corresponding to the north celestial pole; and a straight rule (the alidade), used for sighting objects in the sky. The alidade makes it possible to use the astrolabe for surveying applications; e.g., determining the height of a mountain.

The Atikythera Mechanism

An extraordinary astronomical device dating back to 1st century BC has recently come to light. Remains of the devices were found by divers from a Roman ship wreck more than a hundred years ago at the bottom of the sea near the island of Antikythera – one of the smallest among the Greek Ionian islands. It looked like the remains of a clock-like mechanism, more than 2,000 years old. The find astounded the whole international community of experts on the ancient world. Was it an astrolabe? Was it an astronomical clock? Or was it something else? For decades, scientific investigation failed to yield much and relied more on imagination than the facts.



Parts of the 2,000-year-old Antikythera mechanism remains of which were found from a Roman ship wreck more than a hundred years ago (left) and X-ray tomogram of the same.

Corroded and crumbling from 2,000 years under the sea, the dials, gear wheels and inscribed plates of the device presented historians and scientists with a tantalizing problem.

As soon as the fragments had been discovered they were examined by every available archaeologist; so began the long and difficult process of identifying the mechanism and determining its function. Some things were clear from the beginning. The unique importance of the object was obvious, and the gearing was impressively complex. From the inscriptions and the dials the mechanism was correctly identified as an astronomical device. The first conjecture was that it was some kind of navigating instrument – perhaps an astrolabe. Some thought that it might be a small planetarium of the kind that Archimedes is said to have made. However, research over the last half century has begun to reveal its secrets. From the evidence of the fragments one can get a good idea of the appearance of the original object. Consisting of a box with dials on the outside and a very complex assembly of gear wheels mounted within, it must have resembled a well-made 18th-century clock. The Antikythera Mechanism, as the antique device has come to be known, is a unique Greek geared device, constructed around the end of the 2nd century BC that calculated and displayed celestial information, particularly cycles such as the phases of the Moon and a luni-solar calendar. Nothing as complex is known for the next thousand years.

Researchers used a technique called high resolution linear X-ray tomography and 3-D surface imaging device to unravel the structure and writings on the device. In November 2006, the science journal *Nature* published a new reconstruction of the mechanism by the Antikythera Mechanism Research Project, based on the high resolution X-ray tomography. The new discoveries confirmed that the mechanism is an astronomical analogue calculator or orrery (a clockwork model of the solar system or of just the Sun, Earth, and Moon) used to predict the positions of heavenly bodies in the sky. In July 2008, another paper providing further details about the mechanism was published in *Nature*. This paper, among other things reveals surprising inscriptions on the back dials of the Antikythera Mechanism – including a dial dedicated to the four-year Olympiad Cycle of athletic games in ancient Greece. The Antikythera Mechanism is now understood to be dedicated to astronomical phenomena and operates as a complex mechanical 'computer' which tracks the cycles of the solar system.

Stone and masonry structures

Apart from mechanical devices made of metal, wood, or ivory, some early astronomers relied on massive masonry structures for astronomical observations. Among the oldest such structures is the megalithic ruin known as Stonehenge in England. Stonehenge was constructed of 56 individual

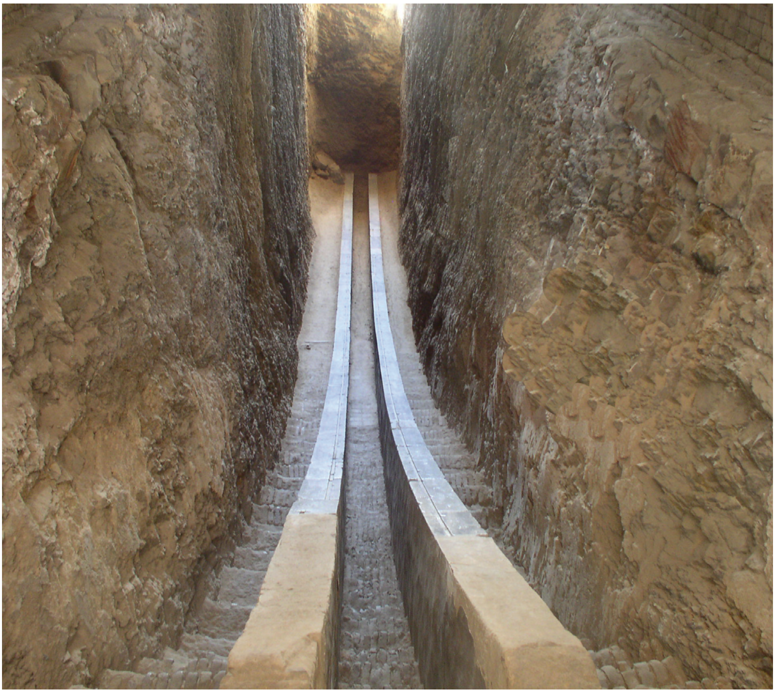
The megalithic ruins of Stonehenge in England was believed to have been used for observation of astronomical phenomena such as summer and winter solstices, eclipses, and more.

segments and was possibly used as a method of determining several astronomical events. Investigations over the last 100 years have revealed that Stonehenge was built in several stages from 2800-1800 BC. It seems to have been designed to allow for observation of astronomical phenomena – summer and winter solstices, eclipses, and more. The stone pillars may have been constructed so that the alignment of the Sun, with respect to the pillars, would allow astronomers to determine the beginnings and the mid-points of the seasons. Stonehenge may also have been used as a tool to determine the position of the Moon throughout the year, roughly predicting the occurrence of eclipses.

In more recent times, one of the earliest astronomical observatories built of stone and masonry was that built by

Ulugh Beg, the grandson of the conqueror Timur, who is also known as Tamerlane. Ulugh Beg was primarily a scientist, in particular a mathematician and an astronomer. He built an observatory on the outskirts of Samarkand in Uzbekistan, the construction of which began in 1428. The observatory, which was circular in shape, had three levels. It was over 50 metres in diameter and 35 metres high. Foundations of the three-story cylindrical structure and underground sections of a giant marble sextant were unearthed by Russian archaeologist Vladimir Viatkin in 1908.

Ulugh Beg's observatory consisted of three gigantic astronomical instruments that dictated the building's structure and layout. The primary instrument was a colossal meridian arc or sextant, running through the building's



Remains of the Fakhri *sextant at Ulugh Beg's observatory in Samarkand.*

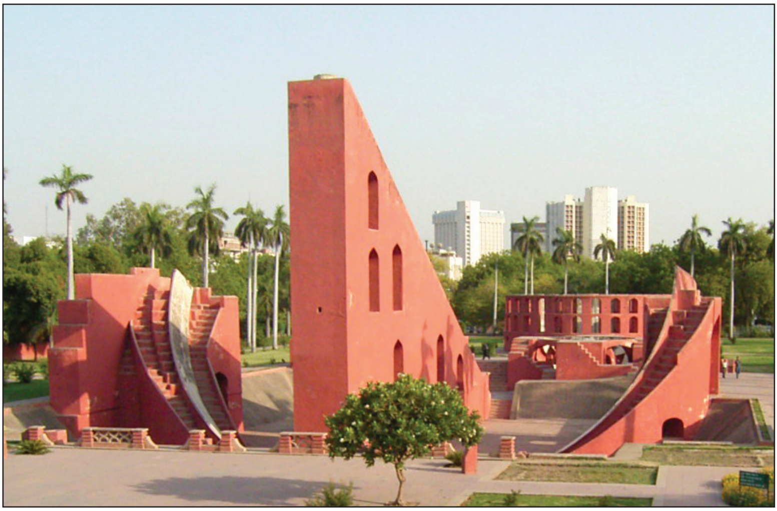
centre, placed along the north-south axis. Lacking telescopes to work with, Ulugh Beg increased his accuracy by increasing the length of his sextant; the so-called *Fakhri* sextant, consisting of two parallel walls faced with marble, had a radius of almost 40 metres and the accuracy of 180 seconds of arc. The giant sextant was simply a sighting device, aligned north-south to the meridian, to observe altitudes of bodies as they crossed the meridian. The results of the observations made under Ulugh Beg included the measurement of the obliquity of the ecliptic as 23° 30′17″ (the actual value at the time was 23° 30′48″) and of the latitude of Samarkand as 39° 37′33″ N. (modern value: 39° 40′). Furthermore, the right ascensions and declinations of the more than 1,000 stars in Ptolemy's star catalogue were verified and corrected.

The observatory of Ulugh Beg was destroyed in the 16th century and completely covered by earth in the course of time; by the 20th century no one knew its exact location. All that remains of the building, now excavated by archaeologists, are the foundations and the lower part of the largest of its scientific instruments, the *Fakhri* sextant.

Jantar Mantars

Ulugh Beg's observatory exerted a large influence on the huge masonry instruments built by Indian ruler Sawai Jai Singh in five Indian cities (most importantly Jaipur and Delhi) in the 18th century, more than 100 years after the invention of the telescope.

Sawai Jai Singh II, the 18th century ruler of the Rajput State of Amber, was passionate about two things – the arts and the sciences, chiefly astronomy. As a scholar he had



Samrat Yantra at Jantar Mantar, New Delhi.

read the works of Ptolemy, Euclid and Persian astronomers. Once, in the court of the Mughal emperor Muhammad Shah, so the story goes, Jai Singh found the Hindu and Muslim astrologers embroiled in a heated argument over certain planetary positions. The positions had to be known accurately to determine an auspicious hour for the emperor to set out on a journey. Jai Singh offered to rectify the then available astronomical tables and was assigned the task of revising the calendar and astronomical tables by emperor Muhammad Shah.

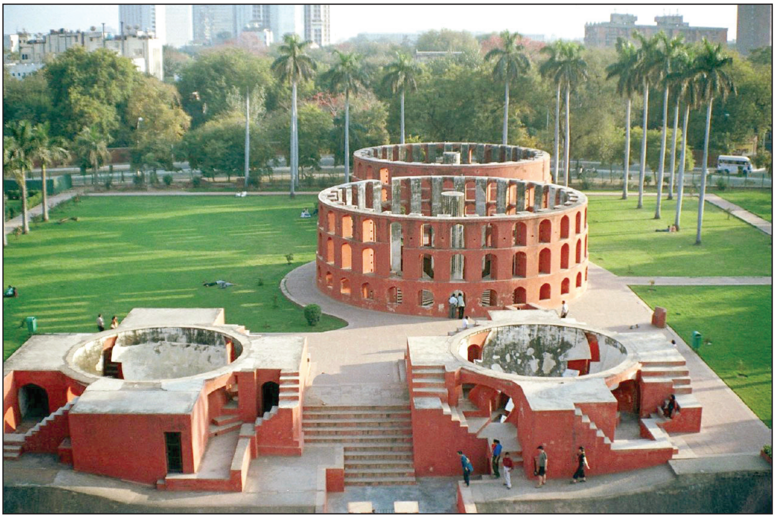
When Jai Singh embarked upon the assigned task, he found several inherent flaws in the brass instruments then in vogue. They were too small and their axes were unstable so the centre often got displaced. So he decided to follow the style adopted by Ulugh Beg in Samarkand. The massive masonry instruments at Samarkand suited Jai Singh's architectural tastes and promised to be more accurate because of sheer size and he decided on masonry structures for his observatories. The first one was built at Delhi in 1724.

Jai Singh called his observatory Jantar Mantar. [Jantar, or *yantra* means 'instrument' while Mantar, or *mantra* is usually translated as 'formula'; but here it means 'calculation'. So, Jantar Mantar literally means something like 'instrument for calculation.'] Astronomical observations were regularly made here and these observations were used for drawing up a new set of tables, later compiled as *Zij Muhammad Shahi*, dedicated to the reigning monarch. The second Jantar Mantar came up at Jaipur in 1734, and the other smaller ones at Mathura, Ujjain and Varanasi between 1732 and 1734.

Incidentally, in 1730, Jai Singh sent a mission to the king of Lisbon. On its return to Jaipur, the mission brought back a telescope. But Jai Singh was not enamoured with the telescope; he had more faith in the accuracy of his huge masonry structures and the versatility of these unique structures bear out his conviction.

Jai Singh's Jantar Mantars are dominated by structures called Samrat Yantra, which are essentially huge equatorial sundials, meant for measuring the time of the day accurate to within a few seconds and the declination of the Sun and other heavenly bodies. Jai Singh himself designed this yantra. The gnomon of the Samrat Yantra at Delhi is a right triangular masonry structure almost 21 metres high at the tip. The hypotenuse of the right triangle is aligned with the Earth's rotation axis. On both sides are two quadrants, which are laid parallel to the Earth's equator in an east-west direction and are marked in hours, minutes and seconds to tell time. The time is reckoned from the position of the shadow of the gnomon falling on the quadrants. The Samrat Yantra is said to be able to measure the time of the day accurate to within a few seconds.

The Jai Prakash Yantra (literally, Maharaja Jai's instrument) is an intriguing instrument, designed by Jai

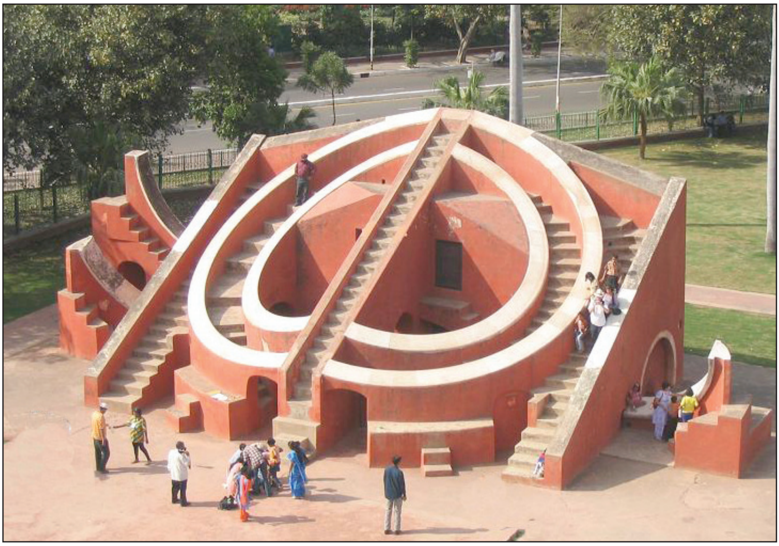


Jai Prakash Yantra (in the foreground) and Ram Yantra at Jantar Mantar, New Delhi.

Singh himself. It was used for verifying the readings of other instruments. It consists of two concave hemispherical marble bowls about 5.5 metres in diameter and representing the celestial hemispheres turned upside down. For the convenience of observation at night the two cavities are divided into six marble slabs, each engraved in minute and second graduations, marking the location of the zodiac signs. The divisions in the two bowls are complementary. When it is used, a metal ring is suspended in the centre with the help of strings stretched across the rim of the bowl. The ring identifies the position of the Sun. During daytime, the shadow of the Sun falls through the metal ring, onto the graduated surface, which allows calculation of time; at night, observers sit inside the slabs of marble and observe celestial objects through the hole in the metal ring.

Another important structure called the Ram Yantra consists of two circular open structures, each with a central pillar. The inside of the circular wall and the floor of each structure are graduated. The floor and the wall in each structure are broken up into a number of sectors in such a way that the two are complementary to one another. Wherever one has solid portions, the other has open spaces. That is, if the two are united together, they become one instrument. This was purposely done to make continuous observation possible. While one instrument shows the shadow cast by the top of the central pillar, the other instrument does not register a shadow. These two structures are used alternately as the Sun moves across the sky. These instruments are used to determine the altitude and azimuth of the Sun. Locating the end of the shadow of the central pillar on the interior floor or wall of the instrument yields the coordinates of the Sun in altitude and azimuth.

Delhi's Jantar Mantar has another masonry structure called Misra Yantra which is supposed to be a multipurpose instrument for astronomical observations. Most experts



Misra Yantra at Jantar Mantar, New Delhi.

believe that the Misra Yantra was not built by Jai Singh but his second son Madho Singh sometime between 1750 and 1754. It comprises five different instruments: (i) the Dakshinottara Bhitti, which is used to measure the zenith distance or altitude of the midday Sun; (ii) the Karakrasi Valaya, the plane of which is parallel to the plane of the Tropic of Cancer. It can be used to determine the summer solstice when the Sun is on the Tropic of Cancer; (iii) the Samrat Yantra, which is much smaller than the main Samrat Yantra and constructed in two halves. It serves a similar purpose – to determine the local time; (iv) the Niyata Chakra, or ‘fixed arc’, which consists of four semicircles attached to a central gnomon, two to the left and two to the right. The gnomon is inclined so as to point directly to the celestial North Pole. This instrument is said to display the meridian circles of four other locations on Earth – four hours east and west and five hours east and west of Delhi. The semicircles are each marked in degrees to give the declination of the Sun on the meridian of these four other locations designated by each of the semicircles. The fifth instrument of the Misra Yantra is an additional quadrant attached to the western gnomon, which is described as the ‘Agra Yantra’. The additional quadrant is used to measure the angle of the Sun at noon on the spring and autumn equinox and on the winter and summer solstice.

The Jantar Mantars built by Sawai Jai Singh II marks the last and the most ambitious attempt at creating large masonry type observatories of the pre-telescopic era. They are monumental architectural ensembles of varying scale and amalgamate the science and religion of 18th century to facilitate measurement of celestial position and movement. They represent the best preserved conglomerate of masonry astronomical instruments in functional condition that continue to serve as a knowledge base for astronomical studies.

2

Optical telescopes

Even as Johannes Kepler was on the threshold of formulating his now-famous laws of planetary motion, based on Tycho Brahe's monumental data and his own naked-eye observations, a new invention was making its appearance in some European cities. It was this ingenious instrument, called the 'spyglass' that would launch astronomy on an entirely untrodden path.

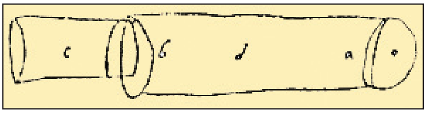
The spyglass itself was nothing new, however. It had been around in Europe for quite some time. For several years lenses of various powers had been available to anyone entering a spectacle maker's shop. Both convex and concave lenses were made routinely by spectacle makers. Convex lenses – lenses that bulged outwards on both sides – were used for seeing enlarged images, mostly by the elderly, for reading. These were aptly called reading glasses. But for those with nearsightedness, who could not see distant objects clearly, convex lenses were not the solution. They needed concave lenses – lenses that curved inward on both sides – that were thinner in the middle than the edges. Objects looked smaller when seen through a concave lens.

Around the turn of the 17th century both kinds of lenses were available in any spectacle maker's shop, but perhaps nobody had thought of putting two lenses of the right focal lengths at the two ends of a tube and looking through it. Finally someone did, in 1608. It must have come about accidentally. Someone must have playfully held a convex lens of low power (with a long focal length) in front of a concave lens of high power (with a short focal length) held close to the eye, and found to his amazement that distant objects appeared to be much closer than they really were. When fitted at the two ends of a long tube, the device could be conveniently used to observe happenings at a distance without being seen. Perhaps for this reason it was called a 'spyglass'. It was the ancestor of the modern telescope.

Although it is generally believed that Dutch lens-maker Hans Lippershey, who lived in Middelburg, invented the telescope, new evidence suggests that the telescope may have been invented in Spain, not the Netherlands or Italy as has previously been assumed. The findings, outlined in the October 2008 issue of the journal *History Today* suggest the telescope's inventor could have been a spectacle-maker based in Gerona, Spain. The first examples may actually have been made for Spanish merchants. The inventor, according to historian Nick Pelling, was probably a person called Juan Roget, who died between 1617 and 1624. The idea subsequently travelled north to the Netherlands, where, in 1608, three separate individuals claimed the invention as their own.

Hans lippershey.

In Holland, Lippershey applied for a patent on 2 October 1608 for a "certain instrument for seeing far," but the patent was eventually denied because it was felt that the device could not be kept a secret. Shortly after that, Jacob Metius of Alkmaar, a city in the north of the Netherlands, also filed a patent application claiming to be the inventor. The claim of yet a third person named Sacharias Janssen, also a spectacle-maker in Middelburg, capital of Zeeland, emerged several decades later. It is thus difficult to decide on the basis of the surviving records, who the actual inventor of the telescope was. All we can say is that Lippershey's patent application is the earliest record of an actually existing telescope.



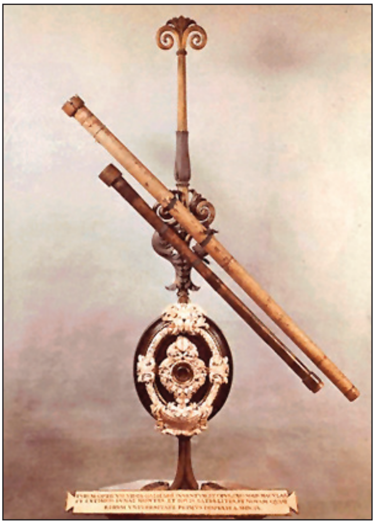
The earliest known illustration of a telescope, from a letter by Giovanni Battista della Porta dated August 1609.

Lippershey's spyglass consisted of a tube of lead at the far end of which was fixed a 'weak' convex lens and to the end nearer to the eye was fixed a 'strong' concave lens. Soon spyglasses became available almost throughout Europe. By 1609, one could buy a spyglass in shops of spectacle makers in London, Paris, Milan or Venice.

Enter Galileo

Italian astronomer Galileo Galilei, who used a telescope to look at the sky and started a scientific revolution.

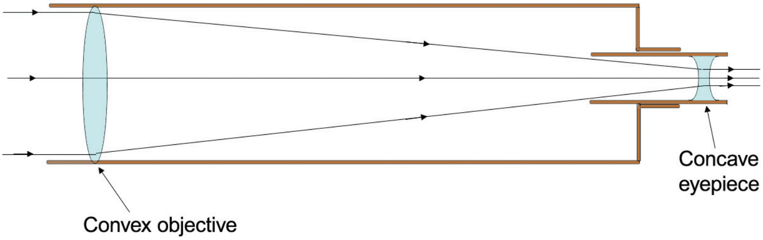
The news of the spyglass also reached the University of Padua, where Galileo Galilei was a professor of mathematics. When Galileo, who had keen interest in astronomy, heard of the spyglass he was thrilled. He immediately got one and, as a true scientist, worked out the working principle using the simple method of ray tracing. He used his knowledge of optics to figure out the mathematical relationship at the heart of the device's power to magnify; it was the ratio of the focal lengths of the objective lens and the eyepiece. Soon, he was able to design and build his own



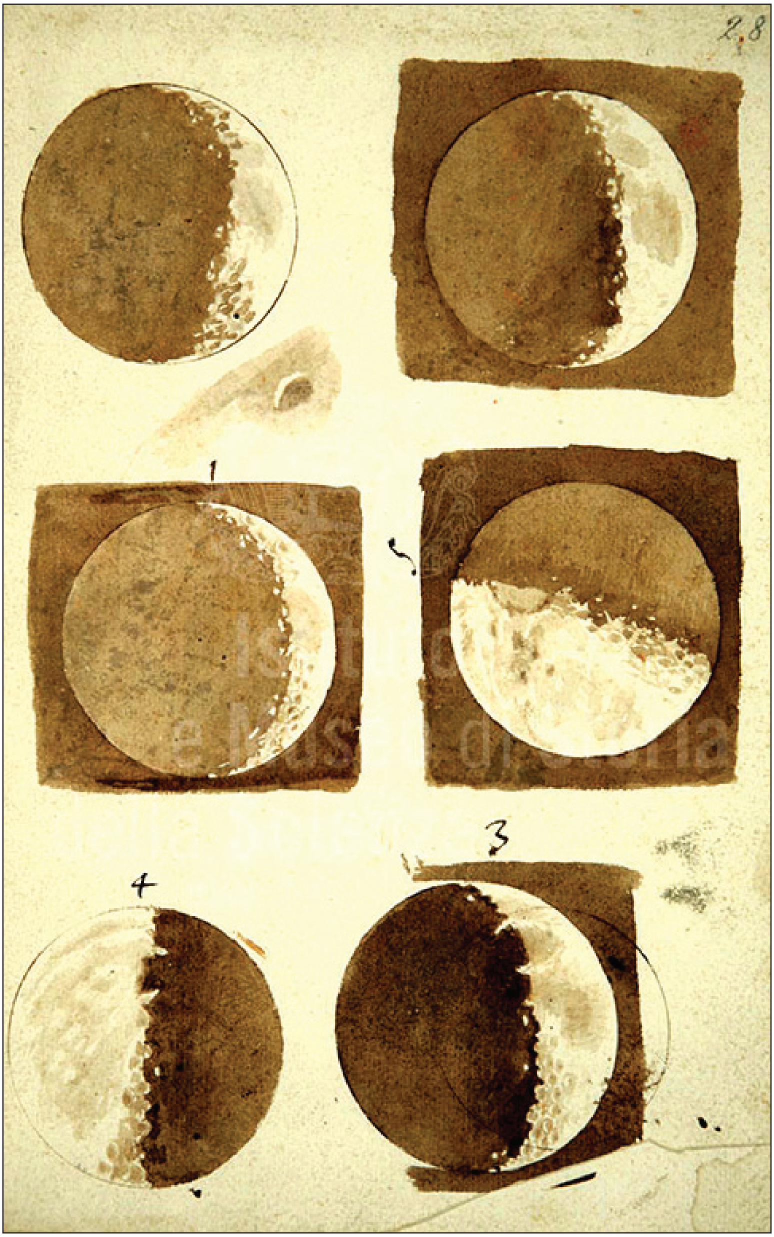
Galileo's telescopes.

telescope of higher powers by grinding his own lenses. During the late summer and autumn months of 1609, Galileo, along with an assistant, continued grinding, and polishing lenses and building longer tubes for his telescopes. By November 1609, he had completed one capable of magnifying about thirty times (30×), almost as good as today's amateur telescopes. After Galileo, telescopes that used a convex lens as objective and a concave lens as the eyepiece came to be known as Galilean telescopes. They are not only simple to build but also produce an upright image of the distant object and so can be used for terrestrial observations also.

But building powerful telescopes was not Galileo's real contribution to astronomy. It was his use of the telescope for observing the celestial objects that really changed astronomy. On 30 November 1609, Galileo began his first telescopic study of the Moon from the garden behind his



Schematic drawing of a Galilean telescope.



Galileo's 1609 sepia wash drawings highlighted the Moon's visible imperfections, which his telescope revealed as mountains and valleys.

apartment in Padua. Unlike today's astronomers who work with photographic camera for recording their observation, Galileo used his pen and artist's brush to draw and paint what he saw. His observations of Moon are meticulously recorded in his sketches, which bring out clearly the surface features of our only satellite.

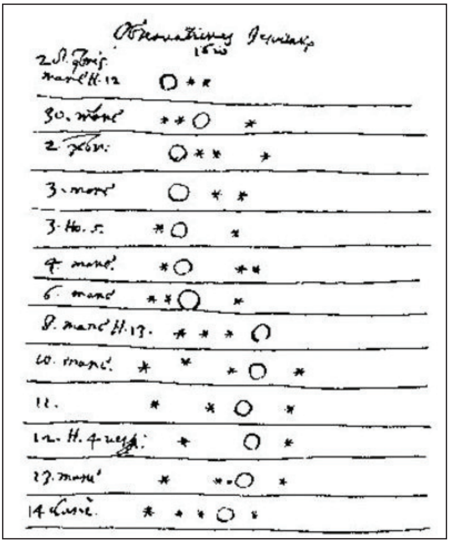
The *Starry Messenger*

In March 1610, barely three months after making his first formal observation of the night sky, Galileo published his findings under the title *Sidereus Nuncius*. The real meaning of this Latin title was a "message from the stars"; but for some unknown reason the English title became popular as *Starry Messenger* or a "messenger from the stars". The book gave an illustrated account of Galileo's new astronomical observations. In the book, he first introduced the new instrument to his readers, "by means of which", he wrote, "visible objects, although far removed from the eye of the observer, were distinctly perceived as though nearby."

About the Moon he wrote, "I have been led to the opinion and conviction that the surface of the moon is not smooth, uniform, and precisely spherical as a great number of philosophers believe it (and the other heavenly bodies) to be, but is uneven, rough, and full of cavities and prominences, being not unlike the face of the earth, relieved by chains of mountains and deep valleys." He mentioned about the "large" or "ancient" spots on the Moon that are visible with the naked eye and about spots "that are smaller in size but so numerous as to occur all over the lunar surface, and especially the lighter part." He also described the uneven, rough, and very sinuous line that divides the sunlit region of the Moon from the dark. He wrote, "not only are the boundaries of shadow and light in the moon seen to be uneven and wavy, but still more astonishingly many bright points appear within the darkened portion of the moon, completely divided and separated from the illuminated part and at a considerable distance from it.”

Galileo was surprised to find the profusion stars when he turned his instrument towards the Pleiades cluster and the Milky Way. In Pleiades, he found as many as forty stars compared to only six or seven visible with the naked eye. The Milky Way turned out to be a conglomeration of multitude of stars. He wrote, “The galaxy is, in fact, nothing but a congeries of innumerable stars grouped together in clusters.”

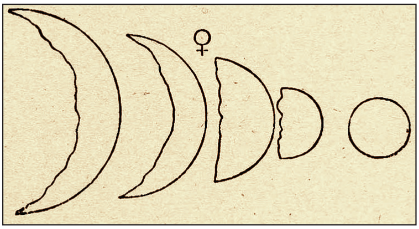
But the most momentous discovery reported by Galileo in his *Starry Messenger* was that of the four moons of Jupiter, which he had erroneously believed to be new planets. He wrote, “There remains the matter which in my opinion deserves to be considered the most important of all the disclosure of four planets never seen from the creation of the world up to our own time, together with the occasion of my having discovered and studied them, their arrangements, and the observations made of their movements and alterations during the past two months.” Of course, he soon realised that they were in fact tiny moons in orbit around Jupiter.



Galileo’s sketch of Jupiter’s moons.

His telescopic observation of the four moons of Jupiter and later, of the changing phases of Venus convinced Galileo that the Copernican system was indeed the more plausible one than the old Ptolemaic model. When observed over a period of several nights, the tiny moons of Jupiter appeared to change position in a manner that could be explained only by taking them to be satellites orbiting the mother planet, which appeared as a disc. Galileo's analytical mind could immediately see a similarity between the moons of Jupiter and the planets orbiting the Sun in the solar system, as set out in the Copernican model.

The second convincing proof of a Sun-centred system came from the observation that Venus showed phases like our Moon. Galileo further observed that, as it changed from a full phase to a crescent phase, its size changed markedly, as would happen if it came near and went farther away from Earth. At the crescent phase, Venus appeared almost six times bigger than at the full phase. If Venus really went round the Earth in a circular orbit, as contended in the Ptolemaic system, such a drastic change in its apparent size cannot be explained. Obviously, Venus was periodically moving away from Earth, when its bright face was visible, and moving nearer to Earth, when its dark side was turned towards us. Both these observations, namely, the changing phase and changing size of Venus could be explained if we presume that the planet goes round the Sun in an orbit which lies inside the orbit of Earth, as per the Copernican model. But we must remember here that both the observations about Venus that Galileo made would not have been possible without a telescope.

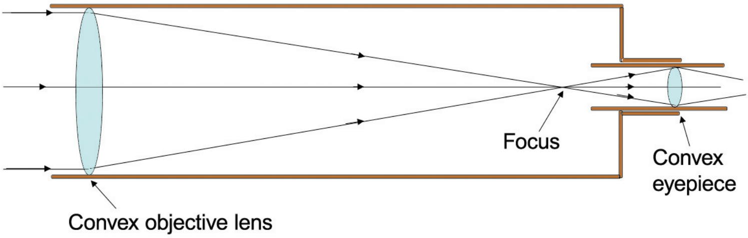


Galileo's drawings of the phases of Venus showing the variation in size.

Kepler's telescope

German astronomer Johannes Kepler designed a better telescope and formulated the laws of planetary motion.

By the time Galileo died in 1642, the telescope had become an indispensable tool for astronomers. But the Galilean design had a serious drawback – the use of a concave lens for eyepiece made the 'field of view' very narrow; that is, one could see only a very small portion of the sky at a time, as if looking through a narrow tube. Galileo's contemporary, German astronomer Johannes Kepler, found a way round the problem by using a convex lens for the eyepiece, which he showed produces a wider, more comfortable field of view. The combination of two convex lenses – one with long and the other with short focal length – gave much sharper images, good magnifications and a reasonable field of view compared to the Galilean instrument. (Kepler is best remembered for his three laws of planetary motion, the first two of which were published in *Astronomia Nova* in 1609, the same year Galileo turned his telescope to the sky.) In the Keplerian telescope the first



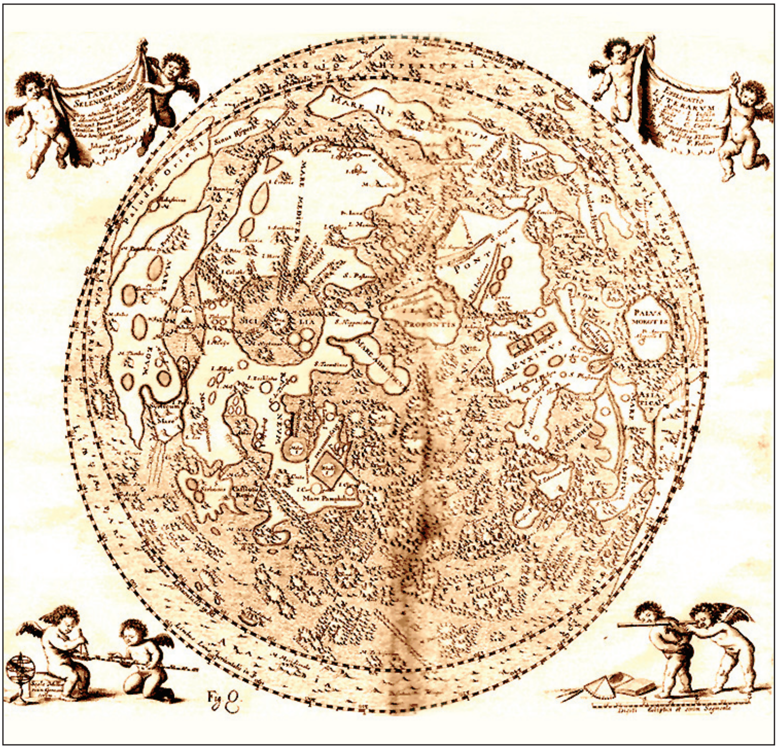
Schematic drawing of Kepler's telescope.

(objective) lens forms a real image of the star or planet, and this image is then magnified by the eyepiece. Kepler first explained the theory and some of the practical advantages of a telescope constructed of two convex lenses in his *Catoptrics*, published in 1611. The first person who actually constructed a telescope of this form was the Jesuit Christoph Scheiner in Bavaria who gives a description of it in his *Rosa Ursina*, published in 1630. It was not till about the middle of the 17th century that the Keplerian telescope came into general use: mainly because its field of view was much wider than in the Galilean telescope.

However, unlike the Galilean telescope, the image produced in Kepler's instrument is upside-down, which makes it only suitable for astronomical purposes. An upside-down image is not a problem for astronomical use, though, because there is no 'up' or 'down' in space, but this prevented the Keplerian telescope from becoming popular for everyday use. Later, a version of the Keplerian instrument with two additional convex lenses to produce an upright image did appear. But this 'terrestrial' telescope was not of much advantage for astronomical observation of the night sky because the extra lenses reduced the brightness of the final image and an upright image of the Moon or the planets were as good as an inverted image.

Kepler's design, although better than Galileo's, also had deficiencies and failed to give clear images. Kepler showed that lenses with strongly curved surfaces gave bad images. Weak objective lenses with long focal lengths were better. The result was the first of generation of very long telescopes. Among them were those built by the German astronomer Johannes Hevelius.

Hevelius's early telescopes, which he used in 1647 for compiling the first atlas of the Moon, measured from 2.5 to



Hevelius's Moon map in Selenographia*. Hevelius gave the features on his Moon maps Earth-like names, such as sea, or "mare" in Latin. Hevelius discovered the Moon's "libration," which is the slight wobble that allows us to sometimes see a tiny part of the Moon's far side. The dotted lines in this image from his 1647 atlas of the Moon, the* Selenographia*, show those areas that are sometimes out of view around the Moon's edge.*

3.5 metres in length. The atlas, *Selenographia*, contained one of the earliest detailed maps of the lunar surface as well as names for many of its features. A few of his names for lunar mountains (e.g., the Alps) are still in use, and a lunar crater is named for him.

The Dutch mathematician and astronomer Christiaan Huygens was among the first to pursue the use of long-focal-length lenses, as shown by Hevelius. With his brother

Constantine, Huygens developed techniques for polishing lenses with small curvatures; that is, long focal lengths. Huygens also invented an improved eyepiece, in which he used two thin lenses instead of a single fat one. The modified eyepiece greatly improved the image quality. The Huygens brothers also invented a grinding and polishing machine that could produce lenses of much better quality. For one of his telescopes Huygens used a lens with a diameter 57 mm and a focal length 3.5 m, which was ground and polished on the new machine. With this telescope he discovered Titan, the largest and brightest of Saturn's moons in 1655. Later that year, with a 7-metre-long telescope, he had partially unravelled the details of Saturn's rings that had so puzzled Galileo. Then in 1656, he used a still longer telescope – measuring 37 metres in length – to confirm his findings. In 1659, he published his *Systema Saturnium*, which for the first time gave a true explanation of Saturn's ring as "a ring, thin, plane, nowhere attached" – based on observations made with his long-focus telescopes.

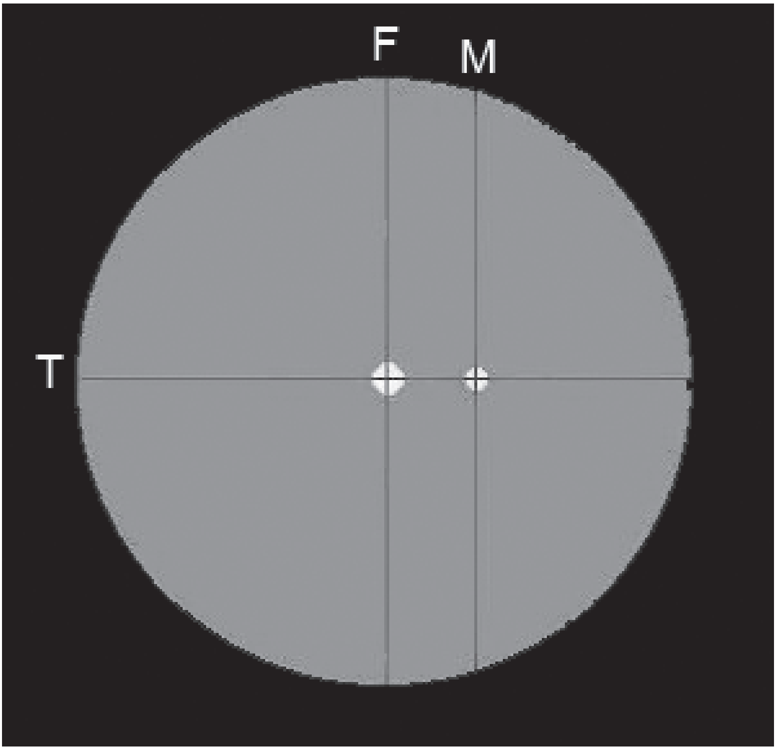
The most successful astronomer among those using very-long-focus telescopes was the Italian astronomer Giovanni Cassini, a professor of astronomy at the University of Bologna. His observations of surface markings on planetary discs set in motion the next phase of the astronomy of the solar system. Along with the English physicist Robert Hooke, Cassini is given credit for the discovery of the Great Red Spot on Jupiter around 1665. Cassini was the first to observe four of Saturn's moons; he also discovered the Cassini Division in Saturn's ring in 1675. Around 1690, Cassini was the first to observe differential rotation within Jupiter's cloud belt. Thus, by the end of the 17th century astronomers had successfully taken the first bold steps in exploring the solar system's planets using long-focal-length telescopes, despite their limitations.

Precision measurements with telescopes

In a Galilean telescope no real image is formed. So there is no way the size of the image or angular separation between two closely spaced stars can be measured. One of the advantages of using convex lenses for both the objective and the eyepiece, as in a Keplerian telescope, was that a real image of the distant astronomical object was formed in front of the eyepiece which was magnified by the eyepiece. A means of measuring the size of the real image was discovered by sheer accident. As William Gascoigne, an English astronomer, recalled in his letters, a spider, quite by chance, spun its web within his Keplerian telescope, exactly at the common focus of the objective and the eyepiece.

This accidental discovery immediately opened up new possibilities of doing measurements with telescopes. A cross-wire placed at the common focus could be used to measure the position of stars in the sky with extremely high precision. Both the image and the cross-wire being at the common focus, both are magnified by the eyepiece, making it possible to measure far smaller angles than the naked eye can even resolve. Besides, the eye does not have to focus separately on the image and the cross-wire.

Gascoigne went a step further and developed the first eyepiece micrometer, which used two fixed fine wires in the field of view of the eyepiece, crossing at right angles, plus a third movable wire, parallel to one of the fixed wires, whose separation could be altered by turning a calibrated screw. Gascoigne realised that by introducing two points, whose separation could be adjusted using a screw, he could measure the size of the image enclosed by them. Using the known pitch of the screw, and knowing the focal length of the lens producing the image, he could work out the size of the object, such as the Moon or the planets, or the separation



A double star pair as seen and measured in a filar micrometer attached to telescope eyepiece. ('T' is the centreline, 'F' is the fixed wire, and 'M' is the movable wire that can be adjusted by turning screws.)

of two closely spaced stars to a hitherto unattainable degree of accuracy.

The device is also known as a 'filar micrometer'. The word filar derives from Latin *filum*, meaning a thread. It refers to the fine threads or wires used in the device. Some micrometers can also be rotated against an angular scale; such a device is known as a position micrometer. Both separation and position angle can then be measured. Filar micrometers are little used in modern astronomy, having been replaced by newer techniques.

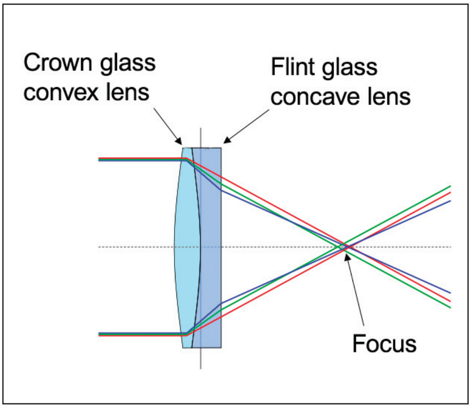
Problems with refractors

A big change in telescope design came from experiments conducted in a darkened room in Cambridge, England. Through a series of experiments performed in 1665 and 1666, the English physicist Isaac Newton was investigating the coloured spectrum produced when a narrow beam of sunlight was passed through a glass prism. He showed that the 'rainbow' of colours was a property of the light, not of the prism, and that white light was combination of light of all colours.

Newton's experiments had great impact on the future of telescope design. The image quality of 17th- and 18th-century refracting telescopes was severely limited because the telescope lenses could not focus the different colours that make up the white light emitted by a star into a single sharp image. Both Galilean and Keplerian telescopes had two major limitations. They suffered from spherical and chromatic aberrations. Spherical aberration is caused by the spherical surface of the lens which prevents light rays from coming to a common focus, causing the image to be blurred or fuzzy. Chromatic aberration is caused by splitting of white light when it passes near the edge of the lens, as through a prism, leading to colour fringes around images. These two problems made it difficult for early astronomers to get clear views of stars and planets. Telescope makers like Hevelius, Huygens and Cassini could reduce spherical and chromatic aberrations by making the convex objective lens with long focal lengths thinner at the edges and. But even thin lenses could not produce completely aberration-free images.

The problem of spherical aberration was later solved by using lenses the surfaces of which are not perfectly spherical but are non-spherical – the so-called aspheric lenses. These were initially difficult to make and often extremely expensive, but advances in technology have greatly reduced the manufacturing cost for such lenses.

The solution to the chromatic aberration was finally found in the form of achromatic lenses (also called 'achromats') that are designed to bring two wavelengths (typically red and blue) into focus in the same plane. The most common type of achromat is the achromatic doublet, which is composed of two individual lenses made from glasses with different refractive indices or dispersing powers. Usually one lens is a convex lens made of crown glass, which has a low refractive index, while the other is a concave lens made out of flint glass, which has relatively higher refractive index. The lens elements are mounted next to each other, typically cemented together, and shaped so that the chromatic aberration produced by one is counterbalanced by that produced by the other. Together the two lenses form a weak positive lens, ideal for a telescope objective.



An achromatic lens is made by joining two individual lenses made from glasses with different refractive indices.

Credit for the invention of the achromatic lens is often given to an English barrister named Chester Moore Hall who pursued optics as a hobby, not as a profession. He is believed to have produced the first doublet achromat around 1729. However, the first patent for an achromatic doublet was awarded to John Dollond, a silk weaver and expert in optics, in 1758 following his independent theoretical and experimental work. In 1765, John's son Peter Dollond found a way to eliminate chromatic aberration altogether, by using a combination of three lenses and producing a triplet achromat. Achromats vastly improved the quality of images and telescopes built with achromats were popular until the end of the 19th century, after which they fell out of favour because of various reasons and made way to reflectors.

One of the main problems with the telescopes with long-focal-length objectives was the relative small diameter of their objective lenses, which produced dim images. The objective lens of a telescope gathers light like catching rain in a bucket. A large-diameter objective gathers more light and produces a brighter image than a smaller objective of the same focal length. So, large achromats could produce images that were brighter and sharper than images produced by thin, long-focal-length lenses and were free from aberrations. But large achromats are very expensive to make because not only has the glass to be pure and flawless – free of bubbles and impurities – because the light has to pass through the lens, the four surface of the two lenses have also to be ground with utmost precision to match perfectly. Further, the larger the lenses are made the heavier they become and in the telescope the lens is supported only along its edge. These constraints put a limit on the size of achromats. The largest refracting telescope in the world, completed in 1897 at Yerkes Observatory in Wisconsin, USA, has a lens diameter of 100 centimetres and weighs 500 kilograms. Larger refractors would be prohibitively expensive.

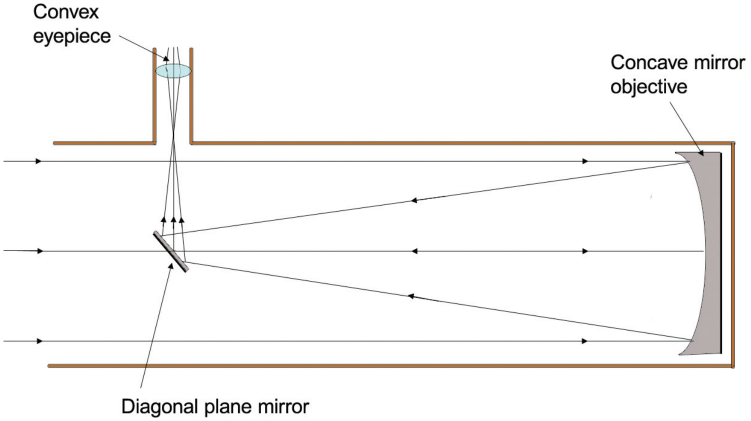
Versatile reflectors

Long before achromats were invented, the English physicist Isaac Newton had come up with a solution to the twin problems of spherical and chromatic aberration of refractors. Because he believed that chromatic aberration could never be eliminated from lenses, Newton turned to reflecting telescopes. His answer was to use a concave mirror, rather than a lens, to collect and focus light. While a simple lens focusses different colours at different points, a mirror focusses all the colours of white light at the same point. Images produced by a mirror thus do not suffer from the defects seen in images produced by a simple lens.

English physicist Isaac Newton was the first to split white light into colours using a prism, paving the way for spectroscopy. He also designed a reflecting telescope using a concave mirror in place of an objective lens.

However, Newton was not the first to suggest use of a mirror in place of a lens. As early as 1616, the Italian physicist Nicolas Zucchi had tried a simple system, and the French mathematicians Martin Marsenne and René Descartes had written on theory of various forms such an instrument could take. James Gregory of Scotland had designed a telescope based on concave primary and secondary mirrors in 1663, but after he came to London in 1665 he was unable to get mirrors of sufficiently precise workmanship. In 1672, a Frenchman, Laurent Cassergrain, invented yet another design using a concave primary and a convex secondary mirror.

But if a mirror is used in place of a lens then another problem arises. In a refracting telescope, as we all know, when light from a distant object passes through the objective lens, an image of the distant object is formed on the other side of the lens, which is further magnified by the eyepiece through which the observer views the magnified image. Here, while looking at the image the observer does not come between the objective and the object. But if a mirror is used as the objective the image is formed on the same side and for viewing it the observer would have to stand between the object and the mirror. Obviously that would cut off all the light from the object! Newton found a simple solution for the problem; he placed a small flat mirror at an angle of 45° inside the prime focus, which deflected the light path to one side of the telescope tube, cutting off only a small fraction of the light falling on the objective. This arrangement made it possible to place the eyepiece in a side tube for convenient viewing, thus obviating any obstruction during viewing. Newton's arrangement was different from those suggested by Gregory, Cassergrain and others.



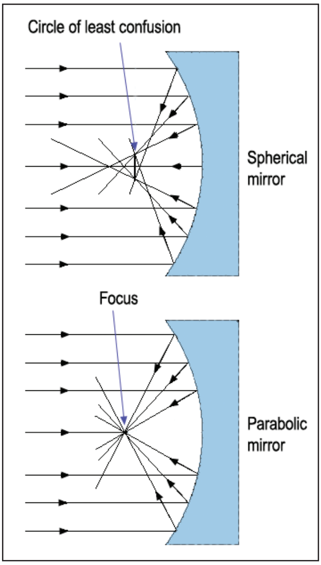
Schematic drawing of a Newtonian reflector.

Newton's reflecting telescope, which he first made in 1668, was a revolutionary innovation in telescope design.

Although small in size – its spherical mirror diameter was 33 millimetres and length only 30 centimetres – it could magnify objects forty times (40×). His instrument roused great interest when he presented it to the Royal Society in 1672. It paved the way for larger and larger telescopes to be built, which saw a tremendous surge in our knowledge about the Universe.

Newton's reflecting telescope.

It was because of the tremendous advantage the reflecting telescope offers that no large refracting telescope has been built in the past hundred years. The world's largest refracting telescope, with an objective diameter of 100 centimetres, was built more than a hundred years ago at Yerkes Observatory in USA. The world's largest telescopes in astronomical observatories today and even the famous Hubble Space Telescope are all reflectors, although of different types.



Light striking a mirror with a spherical surface (top) near its edges and at the centre do not come into focus at the same point, resulting in a fuzzy image. A parabolic surface (bottom) focusses all the rays of light reflecting off the mirror into one focal point making the image sharp.

However, although the reflector telescope managed to correct the main flaw of the refractor telescope called chromatic aberration, it suffered from its own type of spherical aberration. This defect arises because light striking a mirror with a spherical surface near its edges and at the centre do not come into focus at the same point. As a result the image formed is not sharp but fuzzy. The spherical aberration flaw in the reflecting telescope was eventually solved by the 1720s when English mathematician John Hadley taught himself how to grind non-spherical mirrors. He and his two brothers ground a parabolic mirror made of speculum metal (an alloy of copper and tin) for a Gregorian telescope. A parabolic surface rids the problem of spherical aberration by focussing all the rays of light reflecting off the mirror into one focal point where the image is sharp.

William Herschel and his telescopes

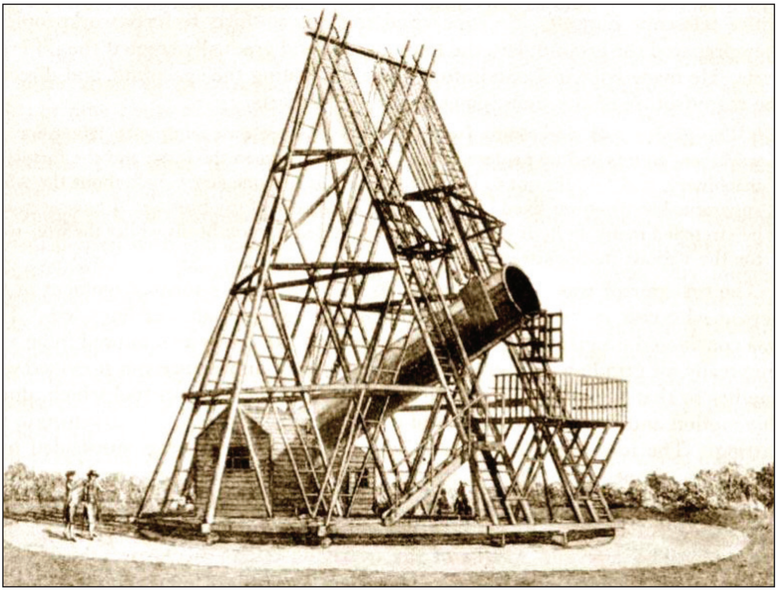
German-born English astronomer William Herschel stands out in the history of astronomy as a remarkable man – the greatest telescope-maker of his time and quite possibly, the greatest observer ever. Through determined efforts to improve the quality of his telescopes, he was able to use the finest equipment of his time, which in turn permitted him to make many significant discoveries about the nature and distribution of stars and other astronomical bodies both within the solar system and beyond.

German-born English astronomer William Herschel was the greatest telescope-maker of his time. He discovered Uranus, the first planet to be discovered with telescope.

Herschel was initially a successful musician, but then began to concentrate on his hobby of astronomy. In 1773, he bought a quadrant and several books on astronomy and started making small telescopes. He made his own mirrors from speculum, as Newton had done, and somehow worked out a way of polishing the hard surface into a reflecting surface of the correct profile to give a good image. His first telescope was a 1.8-metre Gregorian reflector, but it was not a success. His second telescope – a Newtonian – was much better. It showed the rings of Saturn and the Orion Nebula. By 1774, he had made two Newtonian reflectors – one of 11-centimetre aperture and a focal length of two metres, and another of 23-centimetre aperture and a focal length of three metres. In 1778, he polished a speculum mirror about 30 centimetres in diameter. This telescope, which was about 2.1 metres long and of Newtonian design, was the one he used to discover the planet Uranus some 2½ years later. His sister Caroline played an important part in this work. She was closely involved in the telescope making and also the observation work.

Herschel's telescopes produced images of extraordinary quality and he was able to observe and map the sky in unprecedented detail. He made two preliminary telescopic surveys of the whole sky. His first survey was completed in 1779. During the second sky survey, which he started immediately after finishing the first, he concentrated on noting the positions of double stars; that is, stars that appear to be very close together. Then, in 1781, during his third and most complete survey of the night sky, he came upon an object in the constellation of Gemini that he realised was not an ordinary star. He first mistook it for a comet, but it turned out to be the planet Uranus, the first planet to be discovered since prehistoric times.

Herschel's largest telescope, usually referred to as the "Great forty-foot telescope", had an objective mirror diameter



Herschel's great 40-footer. It used an off-axis setting of the objective mirror to produce the image and was the largest telescope in the world for 50 years.

of 120 centimetres and was 12.2 metres (40 feet) long. It was completed in 1789. In this telescope Herschel used an entirely new design in which the primary mirror is tilted so that light is focussed near one side of the open end of the tube. No secondary mirror is used. The eyepiece picks up the focussed light directly, avoiding light loss from reflection by a secondary mirror. This design came to be known as 'Herschelian telescope'. However, this design had a major drawback; since the image is formed off-centre, it suffers from a defect known as astigmatism, unless the focal ratio (the ratio of focal length to aperture) is large. Herschel raised and lowered his 40-foot telescope tubes using cables supported by wood frames. Although the giant telescope got off to a good start, it was not used as much as Herschel's smaller telescopes. It was unwieldy to operate, and because the mirror had a high copper content it tarnished rapidly. The one achievement of the Great forty-foot was the discovery of Enceladus and Mimas, the 6th and 7th moons of Saturn.

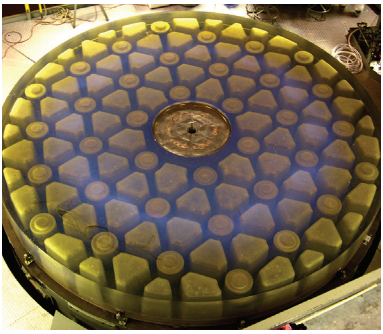
Glass mirrors

Although Newton had built his first reflecting telescope in 1668, not many large reflectors for astronomical observation were built till 20th century. This is because 17th century mirrors, made of speculum metal, did not reflect light with high efficiency, as they got tarnished easily. So the main problem for early reflecting telescopes was to produce an image as bright as one that would be achieved by a lens of the same aperture. The later advances in reflecting telescopes included the perfection of parabolic mirror fabrication in the 18th century, silver-coated glass mirrors in the 19th century, and long-lasting aluminium coatings in the 20th century.

Newton had used speculum metal mirror for his telescope, but in 19th century, reflectors generally used glass mirrors with front-surface silver coating. Although glass was fragile and difficult to cast, it was much easier to handle than speculum alloys. But the most important advantage of using silver-coated glass mirror was the ease of re-coating the reflecting surface. Both silver and speculum metal tarnish in use, but while the silver coating can be dissolved away and replaced with a fresh layer, a speculum alloy surface need re-polishing and any error during re-polishing could distort the curvature and ruin the mirror.

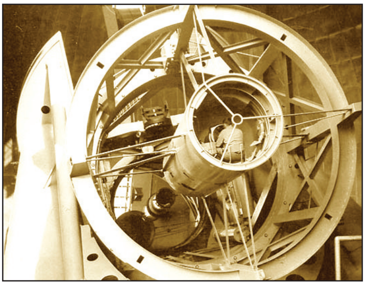
But glass mirrors have had their limitations too. The main problem with large glass mirrors was that they had to be thick for dimensional stability, which increased their weight tremendously and made them difficult to manoeuvre. Secondly, the front-surface silver coating easily got tarnished and needed frequent re-coating. Towards the end of the 1930s, two new technologies emerged that revolutionised telescope making. The first was a method of depositing aluminium, rather than silver, on to glass mirrors. Unlike silver coating, which is deposited by wet chemical process, aluminium coating is done in dry conditions in a vacuum chamber at a temperature of about 540°C by a process known as 'sputtering'. The aluminium coating is much more durable than silver and requires less frequent re-coating.

The second breakthrough was the arrival of a new glass called Pyrex, which was not only much less sensitive to temperature changes than ordinary glass, but was also tougher and could be cast as a hexagonal cellular structure that reduced its weight compared to a solid disc by almost half. Lighter mirrors made the telescopes more manoeuvrable. No wonder, telescope sizes increased rapidly, beginning with the 2.5-metre reflector at Mount Wilson Observatory in USA in 1904, to the 5-metre Hale reflector at Mount Palomar Observatory in San Diego, California, USA in 1950, and a 6-metre reflector at the Zelenchukskaya Astrophysical Observatory in southern Russia in 1966.



The honeycomb structure of modern glass mirrors reduces the weight substantially.

Today almost all of the major telescopes used in astronomical observatories are reflectors, but not all of the same design. Reflecting telescopes come in many design variations and may employ extra optical elements to improve image quality or place the image in a mechanically advantageous position. The primary mirror in most modern telescopes is composed of a Pyrex glass base whose front surface has been ground to a parabolic shape. A thin layer of aluminium is vacuum-deposited onto the mirror, forming a highly reflective front surface. While the Newtonian focus design is still used in amateur astronomy, professionals now tend to use prime focus, Cassegrain focus, and Coudé focus designs.

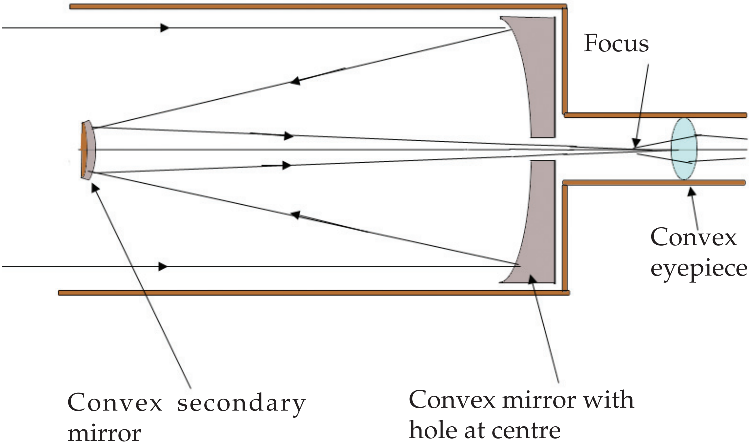


An observer in the prime focus cage of the Hale telescope at Mount Palomar Observatory.

In a prime focus design, the image is formed within the main telescope tube without the use of a secondary mirror. In early days, an observer had to sit inside a cage at the focal point of the reflected light, near the mouth of the telescope tube, to receive the image on a photographic plate. But the space available at prime focus is severely limited by the need to avoid obstructing the incoming light. Nowadays CCD cameras are used for recording the image.

The Cassegrain reflector uses a parabolic primary mirror and a hyperbolic secondary mirror that reflects the light back down through a hole in the primary, converging at a focus behind the main mirror. The use of hyperbolic secondary mirror reduces the length of telescope considerably.

The Ritchey-Chrétien reflector, invented by American optician George Willis Ritchey and French astronomer Henri Chrétien in the early 1910s, is a specialised Cassegrain reflector which has two hyperbolic mirrors (instead of a parabolic primary). It produces high-quality image free of coma and spherical aberration at a nearly flat focal plane if

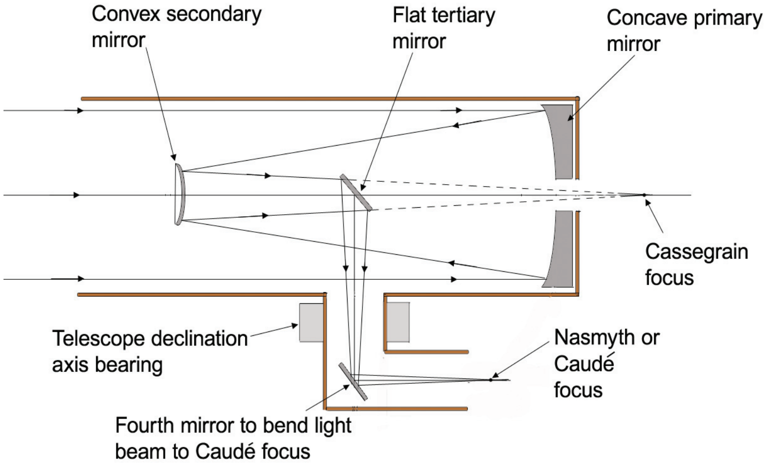


Schematic drawing of a Cassegrain reflector.

the primary and secondary curvature are equal, making it well suited for wide field and photographic observations. Almost every professional reflector telescope in the world is of the Ritchey-Chrétien design.

The Gregorian telescope, invented by James Gregory, employs a concave secondary mirror instead of a convex secondary, and in this way produces an upright image, which is useful for terrestrial observations. Modern telescopes of this design include the 1.8-metre Vatican Advanced Technology Telescope, the 8.4-metre Large Binocular Telescope on Mount Graham in southeast Arizona, USA, and the 6.5-metre Magellan telescopes at Las Campanas Observatory in Chile.

The Nasmyth telescope is a reflecting telescope developed by Scottish engineer James Nasmyth. It is a modified form of a Cassegrain telescope, mounted on an altazimuth mount that allows movement in both vertical



Schematic drawing of a Caudé focus telescope.

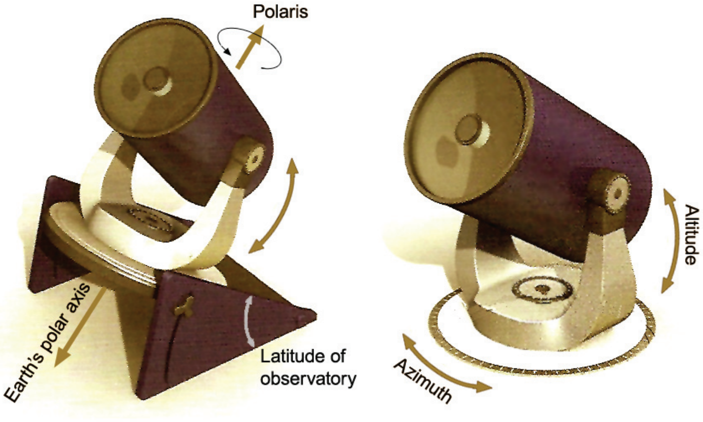
and horizontal axes. As in the Cassegrain telescope, the light falls on a concave primary mirror, then goes to a convex secondary mirror. However there is no hole in the primary mirror. Instead a small flat mirror reflects the light from the secondary mirror to one of the sides of the telescope. This flat mirror is placed on the altitude axis, so that the exit beam comes out of a hole in the middle of the altitude bearing. This means the eyepiece or instrument does not need to move up and down with the telescope.

In many observatories a special telescopic focus called the Coudé focus is used primarily for spectroscopy. This is achieved by modifying the Nasmyth telescope so that the image is formed at a fixed focus point separate from the moving parts of the telescope. This design is often used on large observatory telescopes, as it allows heavy observation equipment, such as spectrographs, to be more easily used. The word comes from a French word meaning 'bent like an elbow,' not from the inventor's name.

Telescope mounts

All telescopes need some sort of mounting for steady viewing. Amateur astronomers use tripods to mount their telescopes, but large telescopes used in observatories needs sturdier mounts that can not only hold the heavy telescope firmly but can also steer it easily for accurate pointing of the instrument. Many sorts of mounts have been developed over the years, with the majority of effort being put into systems that can track the motion of the stars as the Earth rotates with a single motion.

The earliest telescopes used crude mounts that used ropes and pulleys to steer the telescope. In order to point the telescope at a star or planet, it had to be moved both in the vertical (altitudinal) and horizontal (azimuthal) direction, which was quite a complicated affair. This earliest types of mounts are today known as altitude-azimuth, or ‘altazimuth’ systems. But before computerised drives were available altazimuth mounts were difficult to use because adjustment of two angles simultaneously and accurately



Telescope mounts. Equatorial (left) and altazimuth (right).

enough at varying speeds to track an astronomical object was difficult to achieve.

On the other hand, an equatorial mount offers the advantage of tracking by turning the telescope on only one axis adjusted to the local latitude and aligned to the Earth's axis, so that if that axis is turned at the same rate of speed as the Earth, but in the opposite direction, objects appear to sit still when viewed through the telescope. The advantage of an equatorial mount lies in its ability to allow the instrument attached to it to stay fixed on any object in the sky that has a diurnal motion by driving one axis at a constant speed. Most large telescopes built during the 19th century and first half of the 20th century used equatorial mounts.

The main disadvantage of equatorial mounts was their huge in size that needed very large observatory domes. An altazimuth mount is a simple two-axis mount for supporting and rotating an instrument about two mutually perpendicular axes – a vertical (altitudinal) axis and a horizontal (azimuthal) axis. After computers were introduced in the 1970's altazimuth mounts became popular because of their much smaller size that required much smaller domes. As a consequence, most large telescopes built after 1970's have altazimuth mounts and are housed under smaller domes compared to earlier telescopes of the same size or even smaller.

Multi-mirror telescopes

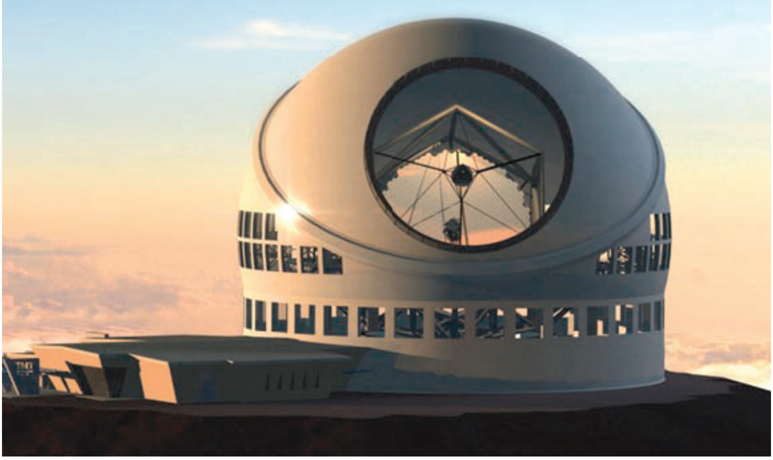
In recent years, a new generation of multi-mirror telescopes has been coming up around the world, thanks to new techniques of computer-aided telescope guidance and electronic image processing. The largest of these is the Very Large Telescope of the European Southern Observatory

Very Large Telescope of the European Southern Observatory (ESO) at Paranal in northern Chile.

(ESO) at Paranal in northern Chile. It is today the world's most advanced optical instrument, consisting of four Unit Telescopes with main mirrors of 8.2-metre diameter and four movable 1.8-metre diameter Auxiliary Telescopes. The telescopes can work together, in groups of two or three, to form a giant 'interferometer', the ESO Very Large Telescope Interferometer (VLTI), allowing astronomers to see details up to 25 times finer than with the individual telescopes. The light beams are combined in the VLTI using a complex system of mirrors in underground tunnels where the light paths must be kept aligned with a deviation of less than 1/1000 millimetre over a hundred metres. With this kind of precision the VLTI can reconstruct images with an angular resolution of milliseconds of arc, equivalent to distinguishing the two headlights of a car at the distance of the Moon!

New generation telescopes

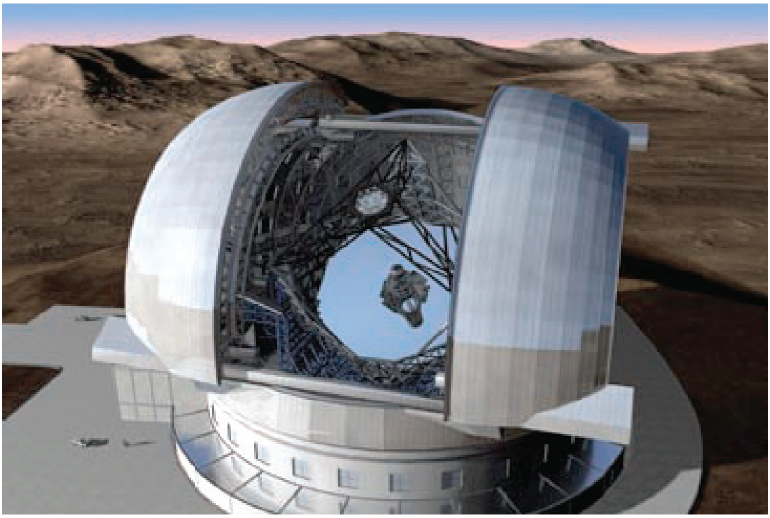
But VLT is not the ultimate in optical telescopes. Three large optical telescopes now at the advanced-planning stage will dwarf even the VLT when completed in 2018.



The Thirty-Metre Telescope, to be located on an isolated mountain peak in the Atacama region of north-eastern Chile, is named after its 30-metre diameter primary mirror, which is made from 492 individual segments.

The Thirty-Metre Telescope (TMT), to be located on an isolated mountain peak rising 4,475 metres in the Atacama region of north-eastern Chile, is named after its 30-metre diameter primary mirror, which is made from 492 individual segments. The telescope will operate in wavelengths from ultraviolet to mid-infrared, enabling astronomers to study the origin and evolution of planets, stars and galaxies. The TMT will seek to shed light on the early Universe, when the first heavy elements formed and will also study small objects in the Kuiper belt, the atmospheres of planets in our solar system, and the connection between supermassive black holes and galaxies.

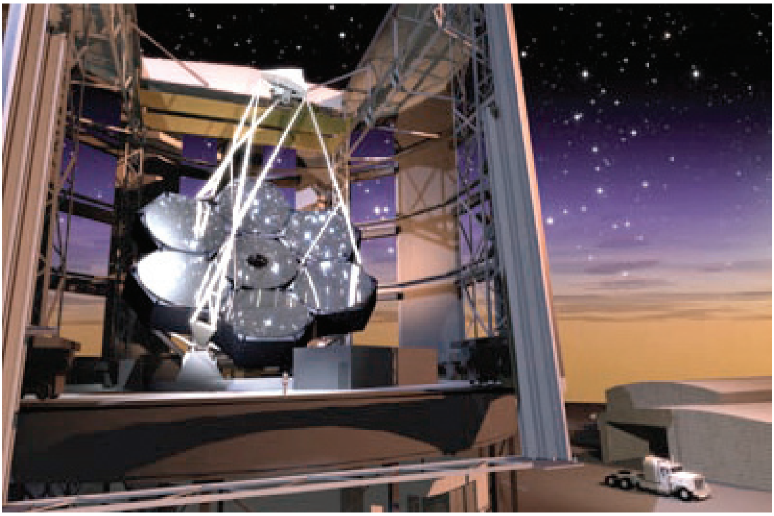
The second large telescope to be built is the European Extremely Large Telescope (E-ELT). The primary mirror of this telescope will be 42 metres in diameter, made of 984 smaller segments that are each 1.45-metre wide. The secondary mirror will be up to 6 metres in diameter. The E-ELT will be sensitive enough to detect reflected light from



The European Extremely Large Telescope with a primary mirror diameter of 42 metres made of 984 smaller segments.

Jupiter-like and potentially Earth-like extra-solar planets, and will try to probe their atmospheres using low-resolution spectroscopy. It will even be able to detect water and organic molecules in gas clouds around stars, thus providing clues as to which planets may become habitable in the future. The E-ELT will be capable of tracking down Earth-like planets in habitable zones around other stars.

The Giant Magellan Telescope (GMT), to be set up at Cerro Las Campanas in Chile, will have a primary mirror consisting of six 8.4-metre diameter individual segments surrounding a seventh central mirror, which will give it the same resolving power as a single mirror with a diameter of 24.5 m. The GMT will be able to gather more than four times as much light as the biggest existing instruments can manage. It will produce images up to 10 times sharper than those obtained by the Hubble Space Telescope and will be used to study planets beyond our solar system, determine



The Giant Magellan telescope, to be set up at Cerro Las Campanas in Chile, will produce images up to 10 times sharper than those obtained by the Hubble Space Telescope.

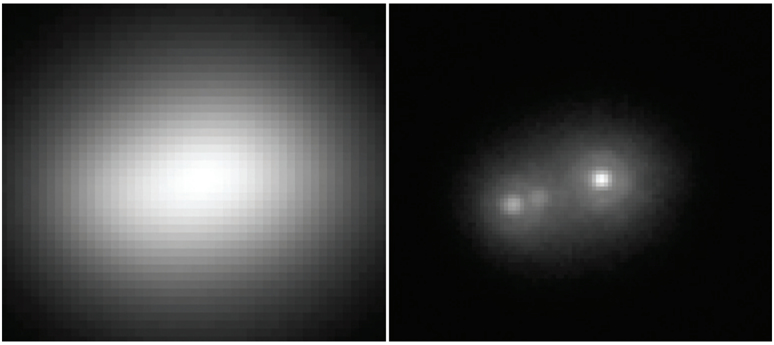
the nature of dark matter and dark energy, study the origin of chemical elements and investigate the growth of black holes. It will operate at visible, near- and mid-infrared wavelengths.

Some of the goals of the Giant Magellan Telescope, the Thirty-Metre Telescope, and the European Extremely Large Telescope are to image extra-solar planets directly, gather emanations from the first stars and galaxies, whose light has been travelling for some 13,000 million years, and investigate dark matter, dark energy, and black holes.

Countering atmospheric turbulence

Even as telescope designs improved and larger and larger telescopes were built, observation from ground was beset with a serious problem – that of atmospheric turbulence.

When light from a star or another astronomical object enters the Earth's atmosphere, atmospheric turbulence (caused by different temperature layers and different wind speeds interacting) can distort and move the image in various ways that leads to blurring of images. To minimise the effect of atmospheric turbulence, astronomical observatories are usually set up high up on mountains. But, still, it cannot be eliminated altogether. Novel techniques are now available for reducing the effect of atmospheric turbulence. Speckle imaging and adaptive optics are two such techniques that have brought about a revolution in ground-based astronomical observation.

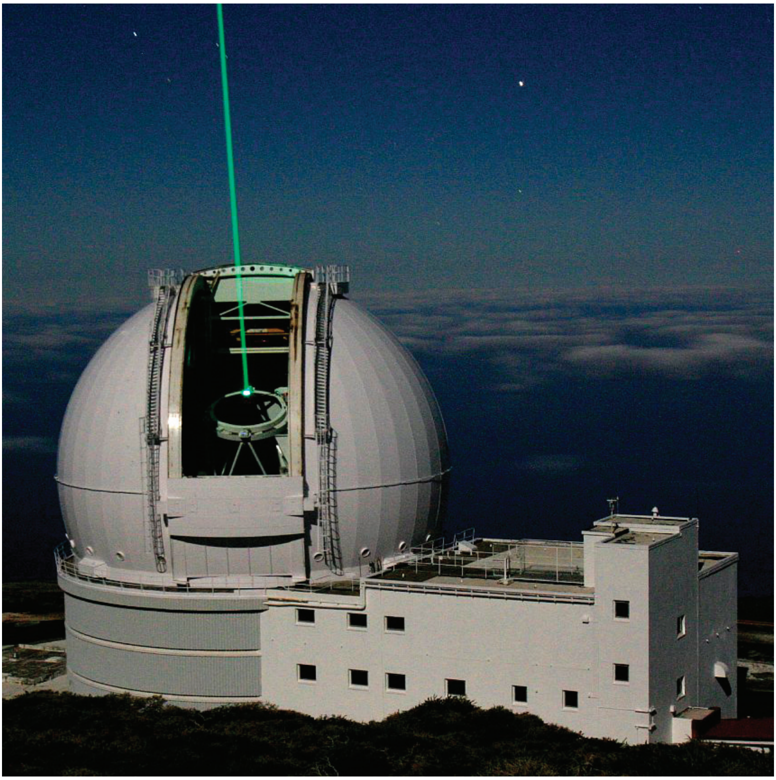


Improvement in image quality by speckle interferometry (right).

'Speckle imaging' describes a range of high-resolution astronomical imaging techniques based either on the shift-and-add ('image stacking') method or on 'speckle interferometry' method. Speckle imaging recreates the original image through image processing techniques, while speckle interferometry involves reconstruction of high-resolution images of astronomical objects from the speckle patterns using Fourier analysis. Both the techniques can dramatically increase the resolution of ground-based telescopes. The principle of all these techniques is to take very short-exposure digital images of astronomical objects, and then process the images to remove the effects of atmospheric turbulence. Use of these techniques have led to a number of discoveries, including thousands of binary stars that would otherwise look like a single star to a visual observer working with a similar-sized telescope, and the first images of sunspots on other stars.

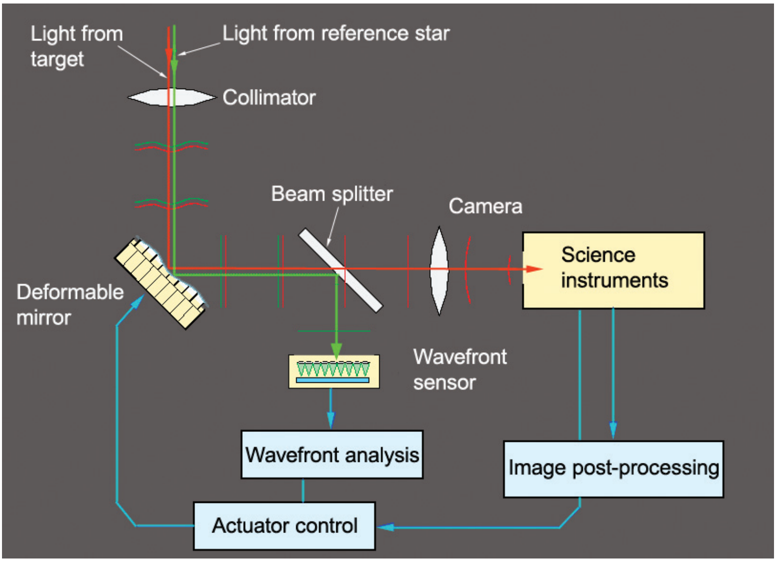
For speckle imaging, hundreds of very short exposures of an astronomical object are made in rapid succession. The digital images, which have a speckled (spotted) appearance caused by atmospheric turbulence, are later analysed using computer to reconstruct a sharp image of the object. One limitation of the technique is that it requires extensive computer processing of the image, which was hard to come by when it was first applied. This limitation has largely disappeared over the years, and nowadays desktop computers have more than enough power to make such processing a trivial task. However, because the exposures must be short and at the same time have good signal-to-noise ratio, speckle imaging is limited to imaging very bright objects. Another disadvantage of this technique is that the results can only be seen following a lengthy reconstruction process.

Adaptive optics improves the performance of optical systems by reducing the effects of rapidly changing optical distortion caused by atmospheric turbulence. In adaptive optics, a deformable mirror is used to correct wave front errors in an astronomical telescope, allowing astronomers to achieve an unprecedented angular resolution in the analysis of faint astronomical sources at optical wavelengths. Adaptive optics was first envisioned by American astronomer Horace W. Babcock in 1953, but it could not be put into actual use until advances in computer technology during the 1990s made the technique workable.



Laser beam to create artificial guide star used as a reference beacon in adaptive optics.

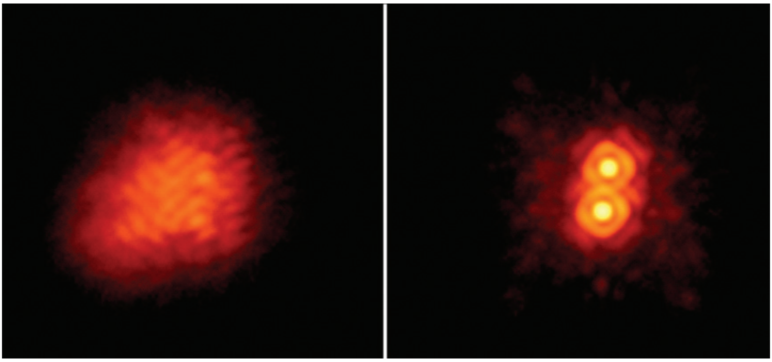
An adaptive optics system uses a point source of light, usually a bright star in the sky – either the same star being studied or a star adjacent to the object of interest, which might be a faint, distant galaxy – as a reference beacon to measure the effects of the atmosphere. In the absence of a bright star in the vicinity of the object of interest, an alternative reference light source, called a ‘laser guide star’, is used as reference beacon. By projecting a laser into the sky astronomers can create an artificial laser-guide star for use in adaptive optics wherever they see fit. To do so, they shine a narrow sodium laser beam up through the atmosphere. At an altitude of about 100 kilometres, the laser



Schematic drawing of an adaptive optics system.

beam makes a small amount of sodium gas glow. The reflected glow from the glowing gas serves as the artificial guide star for the adaptive-optics system.

The light from the reference star is analysed by a detector called a 'wave front sensor' that measures how the light waves were distorted as they passed through the



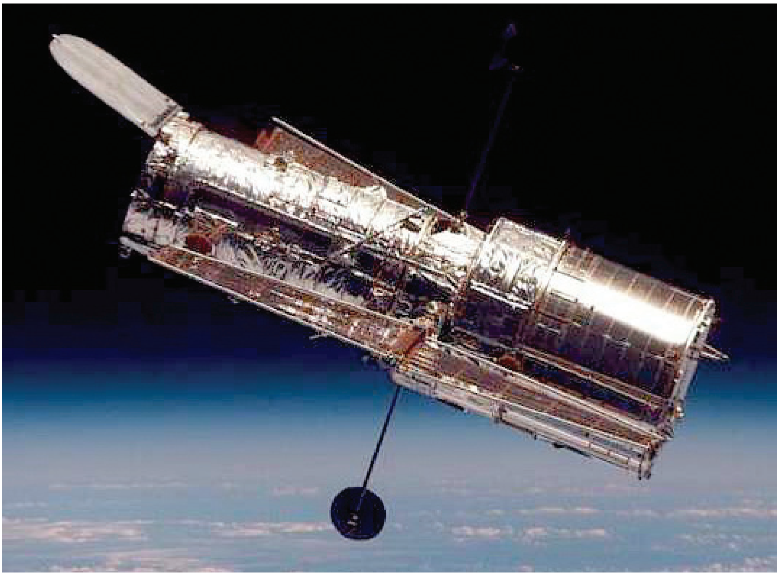
Binary star imaged before and after applying adaptive optics.

atmosphere. The light collected by the telescope is then bounced off a deformable mirror that changes shape to counteract the distortions measured by the wave front sensor. A high-speed computer calculates the necessary corrections several hundred times per second, enabling the system to respond to the constantly changing turbulence of the atmosphere. The improvement in image quality achieved by using adaptive optics is said to be as dramatic as "someone who has had 20/150 vision all his life getting fitted with glasses and seeing the world with 20/20 eyes for the first time."

A telescope in orbit

A new chapter in optical telescopy was opened in April 1990 with the deployment of the Hubble Space Telescope into an orbit 613 kilometres above Earth. It became the first major orbiting observatory, carrying a 240-cm primary mirror with several instrument packages and cameras able to record various parts of the electromagnetic spectrum. The telescope is named after the American astronomer, Edwin Hubble whose work gave the first proofs of the expansion of the Universe.

However, the Hubble Telescope was plagued with problems right from the start. The primary mirror was flawed, which blurred the images and substantially reduced the telescope's ability to see distant stars or objects. In December 1993, astronauts of the space shuttle *Endeavour* captured the Hubble Telescope and corrected the flaw in its primary mirror, and added new instruments. During the second servicing mission by space shuttle *Discovery* in February 1997 some of Hubble's instruments were changed to improve its performance. Two more servicing missions were sent in December 1999 and March 2002 during

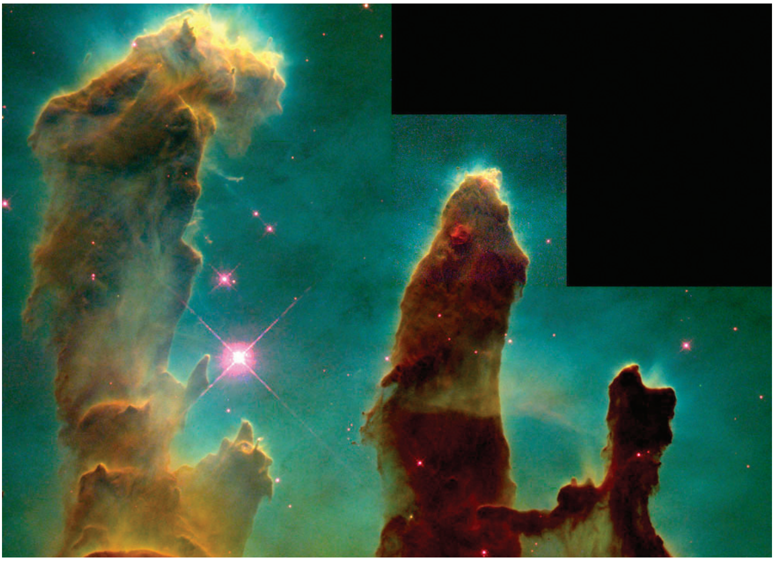


Hubble Space Telescope orbits the Earth at a height of 613 kilometres, far above atmospheric turbulence.

which a new computer and data recorder and an Advanced Camera for Surveys were installed. The fourth servicing mission was completed in May 2009.

During the 19 years in orbit, the Hubble Telescope has seen farther and sharper than any optical, ultraviolet, or infrared telescope before it. Hubble has helped to resolve some long-standing problems in astronomy, as well as turning up results that have required new theories to explain them. Among its primary mission targets was to measure distances to Cepheid variable stars more accurately than ever before, and thus limit the value of the Hubble constant, the measure of the rate at which the Universe is expanding, which is also related to its age. Before the launch of the Hubble Telescope, estimates of the Hubble constant typically had errors of up to 50%, but Hubble measurements of Cepheid variables in the Virgo Cluster and other distant

The Hubble image of the star V838 Monocerotis reveals dramatic changes in the illumination of surrounding dusty cloud structures.

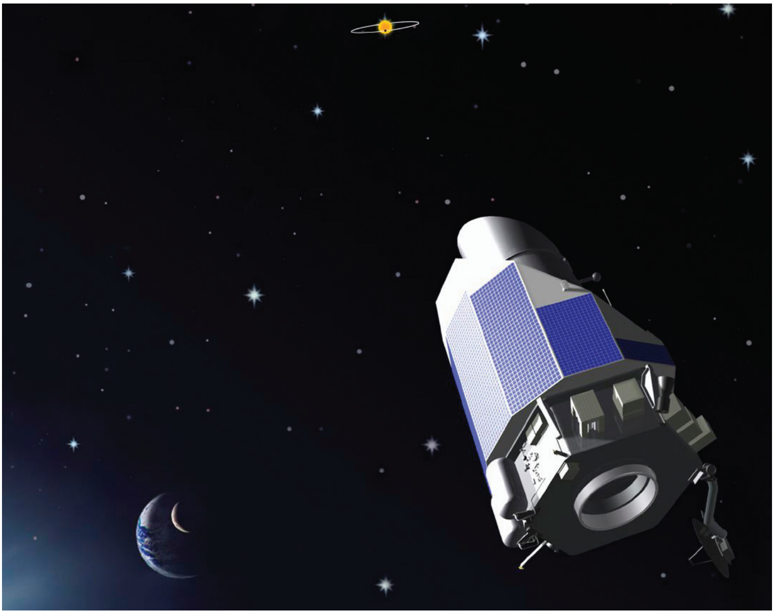


Hubble image of the Eagle Nebula. These eerie, dark pillar-like structures are actually columns of cool interstellar hydrogen gas and dust that are also incubators for new stars. The pillars protrude from the interior wall of a dark molecular cloud like stalagmites from the floor of a cavern.

galaxy clusters provided a measured value with an accuracy of 10%, which is consistent with other more accurate measurements made since Hubble's launch using other techniques. In November 2008 astronomers using the Hubble Space Telescope took the first visible-light snapshot of a planet orbiting another star. The images show the planet, named 'Fomalhaut b', as a tiny point source of light orbiting the nearby, bright southern star Fomalhaut, located 25 light-years away in the constellation Piscis Australis.

Search for Earth-like planets

A unique mission was launched by NASA in March 2009 when a spacecraft especially designed to search for Earth-like planets was launched on a 3.5-year mission. The *Kepler*



Launched in March 2009, the Kepler *spacecraft is designed to search for planets orbiting around other stars by looking for the tell-tale dropping in brightness of a star caused by an orbiting planets' passing in front of it.*

mission is designed to search for planets orbiting around other stars by looking for the tell-tale dropping in brightness of a star caused by an orbiting planets' passing in front of it. In theory, *Kepler* could detect Earth-sized planets that might be orbiting around these stars, and could give preliminary information about any such planets. The spacecraft, named in honour of German astronomer Johannes Kepler, is basically an optical telescope with a 95-cm mirror and a photometer that will continuously monitor the brightness of over 100,000 stars in a fixed field of view from its orbit around the Sun. The data collected from these observations will be analysed to detect periodic fluctuations that may indicate the presence of transiting exoplanets.

Most of the extrasolar planets detected so far by other projects are giant planets, mostly the size of Jupiter and bigger. *Kepler* is designed to look for planets 30 to 600 times less massive, closer to the order of Earth's mass. The method used, the transit method, involves observing repeated transit of planets in front of their stars, which causes a slight reduction in the star's apparent magnitude. When a planet crosses in front of its star as viewed by an observer, the event is called a transit. Transits by Earth-sized planets produce a small change in a star's brightness of about 1/10,000 (100 parts per million), lasting for 2 to 16 hours and this change is absolutely periodic if it is caused by a planet. Precise measurement of such small reduction in brightness can be used to deduce the mass of a planet, and the interval between transits can be used to deduce the size of the planet's orbit. The *Kepler* Mission has a much higher probability of detecting Earth-like planets than the Hubble Space Telescope, since it has a much larger field of view (approximately 10 degrees square).

3

Messages in starlight

The astronomical discoveries till the middle of the 19th century were not much different from the trend in the previous two centuries. The positions of the stars and planets were recorded with precision using simple visual sightings through telescopes. If the objects were larger, such as star clusters and nebulae, they were described in notes, and if of sufficient interest, were drawn by hand. Astronomers had no other means of recording what they saw. In 1609, Galileo used his pen and artist's brush to draw and paint what he saw. His observations of the Moon are meticulously recorded in his sketches, which bring out clearly some of the prominent features of our closest celestial neighbour. Even William Herschel, who built large telescopes and discovered Uranus, recorded what he saw by describing and sketching. But interpretation of what one sees is not always reliable, as is the famous case of 'canals' on Mars. What the Italian astronomer Giovanni Schiaparelli thought to be channels on Mars was an optical illusion, but it created the myth of intelligent Martians and later gave rise to a spate of science fiction stories, including H.G. Wells's famous *War of the Worlds*.

The advances in astronomy that caused the development of modern physics in the first part of the 20th century were of great importance, but in parallel with these there were major developments in astronomy which were the direct result of exploiting the observational power afforded by the photographic plate and the spectrometer. The photographic plate replaced the human eye as the chief detector of starlight while spectroscopy offered a means to analyse the focussed starlight. Together the two techniques became an astronomical tool of such power that a whole new subject – the science of astrophysics – grew from their union. Astronomers now could interpret the physical nature of astronomical objects from their light.

The dagurreotype

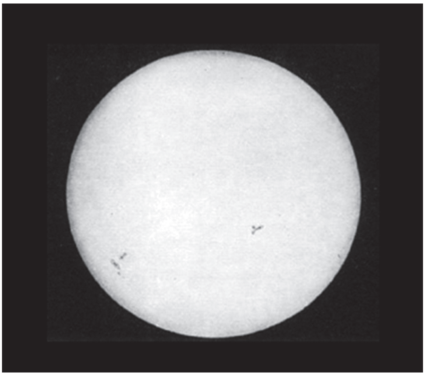
By the end of the 18th century it was known that many silver compounds were blackened by sunlight, and that the black colour was due to the formation of minute particles of silver, which could be used to record 'images' in black and white. But initial attempts were not encouraging, as it was not possible to make a stable, permanent record and it took a great deal of light – often hours of direct sunlight – to produce a modest blackening.

First photograph produced by Joseph Niépce after an eight-hour exposure, showing view from a window.

Interestingly, the first successful attempt to produce a permanent image did not involve any silver compound. It was based on the property of some natural substances such as bitumen to become insoluble when exposed to light. Around 1826, after a great deal of experiment, lasting over ten years, a French inventor, Joseph Niépce succeeded in recording the view from his window as a permanent image. He coated a sheet of pewter (a grey alloy of tin with copper and antimony) with bitumen dissolved in lavender oil and placed the coated sheet inside a camera obscura to capture the picture. After an eight-hour exposure he removed the pewter plate and washed it with lavender oil to remove the unexposed bitumen. The remaining bitumen formed the image, in grey and black, of the view from the window on the plate.

The next big step was taken by French artist, chemist, and photographer Louis Daguerre. Daguerre regularly used a camera obscura as an aid to painting in perspective, and this led him to try to make a permanent record of the image. In 1826 he learned of the work of Joseph Niépce and signed up a partnership with him. After the death of Niépce in 1833, Daguerre continued experimenting in trying to record a photographic image by using paper coated with silver chloride, and in 1835 made an important discovery by accident. He put an exposed silver iodide-coated copper plate, which showed no visible image, in his chemical cupboard. Some days later he found to his surprise that the image was visible. Daguerre eventually concluded that this was due to the presence of mercury vapour from a broken thermometer that 'developed' the 'latent' image. Though he now knew how to produce an image, it was not until 1837 that he was able to fix them by washing the plate with a strong solution of common salt. After years of experimentation, Daguerre announced the latest perfection of his 'Daguerreotype' in 1839.

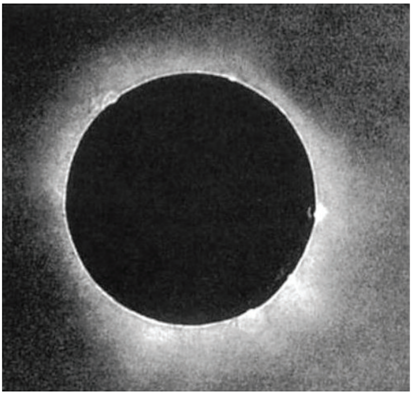
The same year Daguerre and the Director of the Paris Observatory, Dominique Francois Arago made the first attempt at astronomical photography, but with only limited success. Using the equipment of Paris Observatory, they did succeed in blackening a plate by moonlight, but the image was too blurred to show any detail.



French physicists Louis Fizeau and Leon Foucault made the first successful daguerreotypes of the Sun on 2 April 1845. The original image, taken with an exposure of 1/60th of a second, was about 4.7 inches (12 centimetres) in diameter and captured several sunspots.

Because the Daguerre process was so 'slow' it was not until 1840 that the first daguerreotype of the Moon could be made by American chemist J.W. Draper, involving a full 20-minute exposure. The daguerreotype process was further developed in the early 1840s, when it was found that silvered plates that were sensitised with iodine-chlorine or iodine-bromine mixtures were far more sensitive to light than plates sensitised with iodine alone. The exposure time could be reduced considerably – by a factor of 20 or 30. Although this development was of considerable importance for commercial portrait photography, it was not of immediate relevance for the next application for which the Daguerre process was used in astronomy. And this was the photography of the Sun, where the problem was not of sufficient exposure but that of a sufficiently fast shutter to avoid overexposure. French physicists Louis Fizeau and Leon Foucault made the first successful daguerreotype of the Sun on 2 April 1845. The original image, taken with an exposure of 1/60th of a second, was about 12 centimetres in diameter and captured several sunspots.

The faster daguerre process was first applied to astronomy in USA. The Director of Harvard Observatory William Bond and J.A. Whipple, a photographer associated with the Massachusetts General Hospital, obtained the first daguerreotype of the star Vega with a 100-second exposure using a 38-centimetre refractor. Later, much improved daguerreotypes of the Moon were obtained with exposures of only a minute. The last significant use of daguerreotype in astronomy was made during the solar eclipse of 28 July 1851 by a local daguerreotypist named Berkowski who photographed the eclipse from Königsberg in Prussia (now Kaliningrad, Russia) using a 60-millimetre refractor telescope and an exposure of 84 seconds. Berkowski was able to obtain the first correctly-exposed photograph of the solar corona during totality.


First photograph of solar corona taken 1851 by Berkowski.

Collodion plates

Although daguerreotypes produced very clear images, they required lengthy exposures and it was a 'once-only' process; copies of the images could not be made. It was also expensive. British sculptor Frederick Scott Archer's development of the 'wet collodion' process – forerunner of modern photographic film – changed the face of photography; it enabled the making of finely detailed negatives from which multiple copies could be made. This process was the dominant photographic process used between 1851 and 1880. In 1848, Archer had come across a substance called collodion (a syrupy solution of nitrocellulose in a mixture of alcohol and ether, used for coating things), which produced a transparent waterproof film, and which was being used to dress wounds. Archer's procedure was to cover a clean glass plate with a mixture of collodion and potassium iodide dissolved in ether. The ether was allowed to evaporate and, while the collodion was still tacky, the plate was immersed in a solution of silver nitrate, which reacted with the potassium iodide to precipitate insoluble silver iodide. The resulting silver iodide-impregnated collodion was sensitive to light. Both the exposure and the development had to be made in the camera whilst the plate was still wet. Once exposed and developed the collodion-coated glass plate would dry to give a permanent negative from which positive prints could be made.

While cumbersome and tricky, the wet process was much more sensitive than a daguerreotype, able to record light from stars and other celestial objects. It reduced the required exposure time to a few seconds. But until the invention of the gelatin dry plate process in 1871, photography remained a complicated business which could only be carried out by specialists. In the 1880s this "dry plate" allowed much shorter exposure times, and photography became widely known.

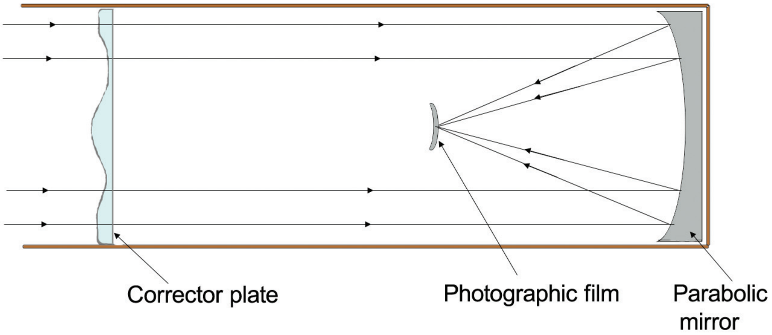
Astrophotography

Although, by early 1850s photographs (daguerreotypes) of the Sun, Moon, and a few bright stars were obtained, real astrophotography started with the availability of the so-called 'portrait objectives' – special lenses that were developed primarily for portrait photography. The distinctive feature of these lenses was their medium focal length and large aperture, with the ratio between objective diameter and focal length of up to 1:5. Such large focal ratio made portrait objectives very fast and with a large field of view, which made astrophotography quite rewarding. Astrophotography offered several advantages not available earlier. Even celestial objects not visible to the naked eye could be photographed with time exposure. A further advantage was that in contrast to the direct measurement at the telescope, the photographic plates could be convenient analysed in the laboratory and also could be saved for later comparisons.

Since early 20th century, special photographic objectives, with the ratio between objective diameter and focal length of about 1:10, have been developed for astronomical purposes. Fast glass reflectors with short focal length (the ratio between objective diameter and focal length of 1:8) can resolve individual stars in some galaxies; however, their field of view is much smaller than that of portrait lenses. Since 1900, reflectors have gradually established themselves, but only since 1930 has it been possible to image large fields of the sky without distortion with a Schmidt Telescope.

For a wider view

Astronomical studies in the early 20th century were mostly confined to photographic methods to record images of astronomical objects at the focus of the telescope. However, most telescopes of those days, which used parabolic mirrors as objective, could cover only a tiny fraction of the sky; most had a field of view no larger than



Schematic diagram of a Schmidt telescope, which uses a spherical mirror and a transparent 'corrector plate' to vastly increase the field of view.

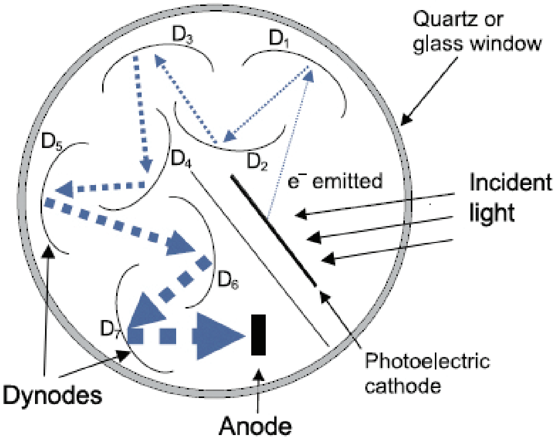
about 1° of arc across. The breakthrough came in the 1930s, with a design developed by Bernhard Schmidt in Germany, who used a spherical mirror and a transparent 'corrector plate', which vastly increased the field of view. The first Schmidt telescope, completed in 1930, had a field of view of as large as 16° across. At the same time, photographic plates also became progressively more sensitive to an ever-widening range of colours. A 1.2-metre Schmidt telescope at the Hale Observatory on Mount Palomar in USA was used in the 1950s for a photographic sky survey, which still remains the standard reference atlas of the sky of the Northern Hemisphere.

Despite the many advantages it offered to astronomers, the photographic method had its own limitations. For example, the photographic emulsion did not show a linear response to the intensity of light falling on it if the intensity was very low. As a result, photographs of very faint objects not only took a very long time to record but also did not always bring out the subtle differences in brightness of faint objects. Fortunately for the astronomers, help was already on way, in the shape of electronic light detectors, which made use of the phenomenon called photoelectric effect.

Photon power

The photoelectric effect, discovered by Albert Einstein in 1905, soon came to be used in a wide variety of detectors the simplest of which was the photocell. In this device the incident light fell on a sensitive surface called the photocathode, housed within an evacuated glass tube. The ejected electrons travelled across the evacuated space to a collecting electrode, also sealed within the evacuated tube. The intensity of the stream of electrons produced, which could be measured using a highly sensitive ammeter, was directly proportional to the intensity of the incident light.

The coming of the photocell opened up a new horizon in astronomical studies of the sky. The photocell was first used for astronomical studies in 1924 by a German astronomer named Paul Guthnick and was soon followed by others to study the stars. But the signals received from a photocathode (a cathode that emits electrons when illuminated), except for the very bright stars, were too faint

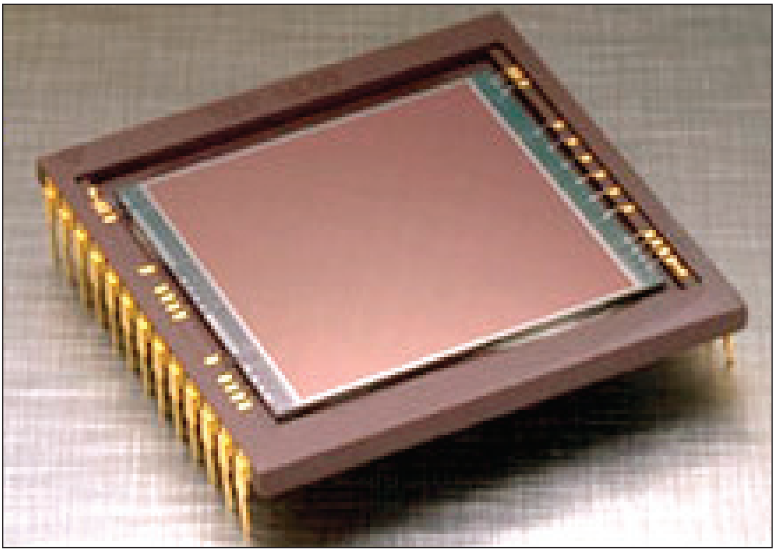


Photomultiplier tube can multiply the flow of photoelectrons by more than a million times.

to be measured. The solution of the problem was found in the form of what came to be known as the photomultiplier tube – the heart of a photoelectric photometer.

The photomultiplier tube is an enhanced version of the phototube, with a series of electron-emitting plates (dynodes) that act as electron multipliers. When light hits the first photocathode electrons are emitted. These electrons are accelerated towards the second plate, which in turn ejects more electrons that move towards the third plate and so on. This process of multiplication is continued for several more stages till a flood of electrons are received at the anode. Frequently, magnification of a million times in the flow of electrons is achieved in a photomultiplier tube. The output is sent to a recorder or a digital storage device to produce a permanent record. Despite its high sensitivity and linear relationship between the number of electrons released and the intensity of light falling on it, however, the photomultiplier tube had a major disadvantage. Unlike a photographic plate, the photomultiplier tube could be used to record only one object at a time.

A better solid-state device known as the charge-coupled device or CCD, which made its appearance in the 1980s, has today replaced the photomultiplier tube in astrophotography. It uses a light-sensitive material on a silicon chip, arranged in two-dimensional arrays of tiny picture elements, or pixels, which can receive an image over a much larger area than is possible with a photomultiplier tube. One can think of the CCD as having a 2-D array of thousands or millions of tiny photocells, each of which transforms the light from one small portion of the image into electrons. The amount of charge depends on the intensity of the incident light. The more the light hitting a diode, the greater the charge it records. A CCD also contains



Megapixel CCD is a highly sensitive solid-state device that has mostly replaced the photographic plate in astrophotography.

integrated microcircuitry required to transfer the detected signal along the pixels and thereby scan the image very rapidly. Pixels can be assembled in various sizes and today megapixel CCDs are quite common .

The main advantage of the CCD is its extreme sensitivity. It is 100 times more sensitive than the photographic plate and so has the ability of recording images of fainter objects with very brief exposure. Another positive feature of the CCD is that the detector material may be altered to provide more sensitivity at different wavelengths. The images can also be processed electronically to bring out better contrast and colour. These advantages as well as the digital nature of the data make CCD devices ideal for astronomical imaging. Today, most large observatories use CCDs to record data electronically (as do the new digital cameras, which do not use film). CCDs also provided a reliable mode of recording and transmission of images taken from space to ground stations. The Hubble Space Telescope with a 2.4-metre mirror, which was launched in 1990, carries CCD detectors that have sent back thousands of images of solar system planets and deep space objects, which are of unprecedented quality.

Measuring the brightness of stars

Even a cursory glance at the night sky would reveal the wide variation in the brightness of stars. Sirius, the brightest star in the sky, shines with dazzling white light while there are faint stars that cannot be seen with the naked eye. More than 2,000 years ago the Greek astronomer Hipparchus divided the naked-eye stars into six brightness classes. The brightest visible stars he called stars of the first magnitude and the faintest visible he called stars of the sixth magnitude. But this was not a very accurate method of measuring brightness of stars because the human eye cannot detect differences of brightness less than 10%.

After 1850, photography was used to determine the brightness of stars, as the density and size of the image is directly related to the brightness of the star. But it was soon apparent that the photographic magnitudes did not agree very well with those obtained visually. The reason for this is that early photographs responded mainly to blue light whereas the eye responds best to greenish-yellow, and stars appear in different colours; some stars appear reddish, others bluish and this difference causes the determined brightness to be different. The modern successor to the photographic plate, the CCD, is capable of measuring individual photons from stars and galaxies. By counting these photons, astronomers can directly compare the light intensities received from individual stars.

Other devices are available which can measure the brightness of an astronomical object in X-ray, ultraviolet, infrared and in radio wavelengths. Some of these have to be used above the Earth's atmosphere, in rockets or satellites, because radiation of these wavelengths does not pass through the atmosphere.

Variable stars

Apart from bright and dim stars there are also stars that show a change in brightness over a period of time – in a matter of hours, days, or weeks. Ancient sky watchers knew of many such 'variable stars' but they did not know why their brightness changed over time. There are some variable stars that are bright enough to observe with the naked eye or a pair of binoculars. Some variables may be so faint at minimum that it is not possible to observe them without a telescope. After light measuring devices became available it was possible to measure the brightness change of variable stars more accurately.

Variable stars, the brightness of which varies widely, can be easily observed visually. But for some variable stars, the fluctuations are much more subtle and require higher precision instruments such as photoelectric photometers or CCDs for observation. It is possible to study fainter stars with a CCD than visually with the same telescope.

Variable stars fall into two general categories: (i) intrinsic variables, in which physical changes, such as pulsations or eruptions are involved; and (ii) extrinsic variables, in which the light output fluctuates due to one star eclipsing another. Cepheid variables are a special type of variable star. They are intrinsic variables; that is, their brightness actually increases and decreases with time. They are named for the star Delta Cephei, the first of these pulsating stars detected in 1784 by British astronomer John Goodricke. Astronomers have discovered over 700 Cepheid variable stars in our Milky Way galaxy, and several thousand in the Andromeda, and the Magellanic Clouds.

The discovery of Cepheids opened up a new chapter in astronomy – in measuring astronomical distances – after the path-breaking work of English astronomer Henrietta Leavitt. Leavitt discovered more than 2,400 variable stars, about half of the known total in her day. Through these discoveries came her most important contribution to the field: the study of Cepheid variable stars in the Magellanic Clouds – the two companion galaxies of our Milky Way, which are seen in the southern sky. By intense observation and mathematical calculation, Leavitt realised that the maximum brightness of a Cepheid variable was directly related to the period of its fluctuation – the slower the fluctuation of its brightness, the brighter it was. Since the Cepheids in the Magellanic Clouds were all about the same distance from Earth, Leavitt concluded that the period, or time it took to complete one cycle of dimming and brightening, was related to the star's intrinsic brightness or magnitude. So, if the fluctuation period could be measured accurately, the absolute magnitude of the star could be deduced, and by comparing it with the brightness as it appears from Earth (apparent brightness), the distance to the star could be calculated. Cepheid variables thus could be used as 'standard candles' for measuring distance of stars.

Leavitt published her findings in 1912 – in a chart of 25 Cepheid periods and their absolute brightness. Using this data, astronomers only needed to know the period of a Cepheid variable to figure out how bright, and therefore how far away it was. Until then, methods for measuring distances of stars only worked within about 100 light years.

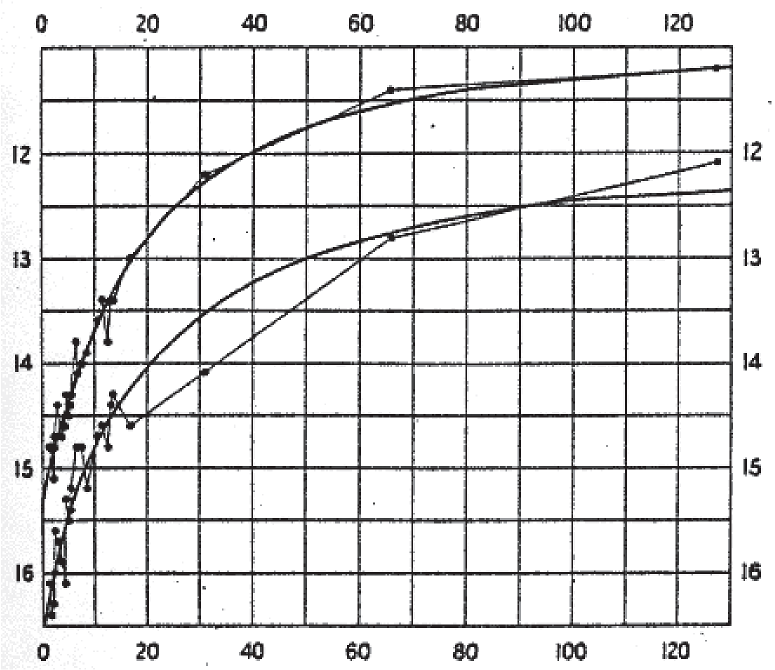


Chart of 25 Cepheid variable stars prepared by Henrietta Leavitt, showing relationship between periods (x-axis) and their absolute brightness (y-axis).

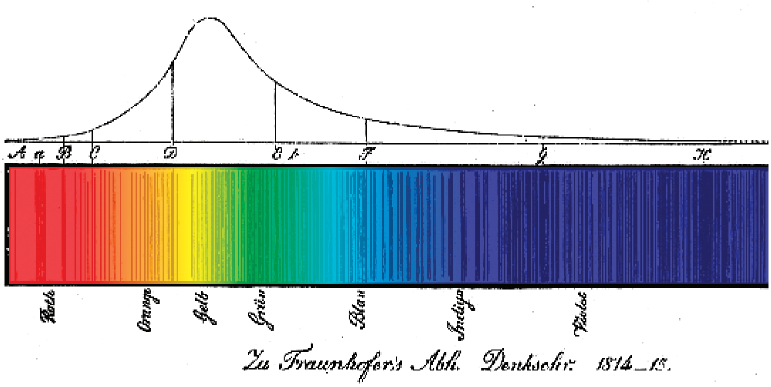
With Leavitt's findings, distances of Cepheids could be determined up to 10 million light years. This became the "yardstick to the Universe" used by Edwin Hubble and others to make discoveries that changed our view of our galaxy and the Universe.

Spectroscopy

Spectroscopy is second to photography with regards to its importance in astronomy. It was the photography of spectra that gave birth to astrophysics. A spectrum is the result of splitting up light into its constituent colours and it is by studying spectra that astrophysicists have been able to make their most important discoveries. The most familiar spectrum in nature is that splendid spectacle, the rainbow, which is produced when light from the Sun is split into its constituent colours when it bounces around inside each of millions of raindrops. In laboratory scientists use a triangular glass prism, or more commonly nowadays a device called a diffraction grating, to disperse the light into a spectrum. The whole apparatus for doing this job is called a spectroscope (if one observes it visually), or a spectrograph (if the spectrum is recorded photographically or by some means other than the eye). All modern spectrographs use diffraction gratings.

Although the first spectrum was obtained by Isaac Newton in 1666 when he passed sunlight through a glass prism, spectroscopy really took off when in 1814 the German astronomer Joseph von Fraunhofer took spectra of the Sun by mounting a prism in front of the objective lens of a small telescope and passing the sunlight through a thin slit before allowing it to fall on the prism. Modern telescopes use sophisticated spectrographs for photographing and recording spectra of astronomical objects.

Fraunhofer was a lens grinder and was employed by the famous Munich Philosophical Instrument Company, one of the most prominent suppliers of scientific optical equipment in the world. There he was able to exercise his glass working abilities, producing lenses and prisms of unprecedented clarity. He rapidly gained a reputation for constructing lens systems free of colour flaws (such lenses were vitally important to astronomical observing). It was while he was perfecting his lenses that Fraunhofer made what was to be his most important discovery. In order to calibrate his instruments he would use a bright candle. One day, however, he chose to use the light from the Sun. He was quite surprised to find a number of dark lines crossing



When Joseph von Fraunhofer took spectra of the Sun by passing sunlight through a prism he got a spectrum with 574 individual dark lines, now called Fraunhofer lines.

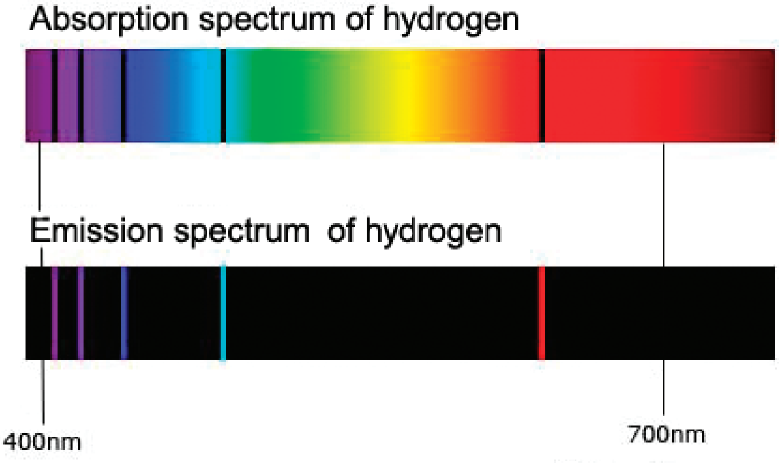
the Sun's rainbow spectrum – lines that were not present in the spectra of candlelight. He was able to discern some 574 individual dark lines in the spectrum of the Sun, which came to be known as 'Fraunhofer lines'.

Between 1855 and 1863, German physicist Gustav Kirchhoff and chemist Robert Bunsen experimented with laboratory chemical spectra and discovered that each chemical element has its own unique spectral signature – a set of lines in the spectrum called spectral lines. This provides a sort of 'fingerprint' which can confirm the presence of that element. Probably the most familiar of the characteristic emissions from a common element is the yellow-orange light emitted by sodium vapour. Almost all of the light from a sodium vapour street lamp comes out in two very close lines in the yellow-orange part of the spectrum; this same element is also responsible for the yellow colour produced when, for example, common salt (sodium chloride) is sprinkled on the blue flame of a Bunsen burner.

One evening Kirchhoff and Bunsen saw, from the window of their laboratory in Heidelberg, a fire raging in the port of city of Mannheim 16 kilometres to the west. Using their spectroscope, they detected the telltale spectral lines of barium and strontium in the flames. Kirchhoff and Bunsen recognised that this could be a powerful tool for "the determination of the chemical composition of the Sun and the fixed stars." They further deduced that the dark lines in the solar spectrum were caused by absorption by those elements in the upper layers of the Sun. During the 1860s, Kirchhoff managed to identify some 16 different chemical elements among the hundreds of lines he had recorded in the Sun's spectrum. From those data, Kirchhoff speculated on the Sun's chemical composition as well as its structure.

Spectra can be of two types – emission spectra and absorption spectra. Emission spectra are produced from light emitted by atoms when they are excited, as in a hot gas. Flame test for salts would also produce emission spectra consisting of bright lines of wavelengths characteristic of the particular elements present in the salt, seen against a dark background. On the other hand, absorption spectra are produced when white light produced by a hot source is passed through a cooler gas and consist of dark lines at wavelengths characteristic of the elements present in the cool gas in the background of a continuous spectrum. The interesting thing is that the spectral lines of any particular atom are seen in the same positions in both emission and absorption spectra; the only difference is that in the former the lines are bright and are seen against a dark background while in the latter the lines are dark lines and appear in the background of a bright continuous spectrum of white light.

Spectroscopy allows astronomers to do much more than merely identify chemical elements. It is from spectroscopic studies that astronomers have been able to determine that hydrogen is by far the most common element in the Universe


Absorption spectrum of hydrogen
Emission spectrum of hydrogen
400nm
700nm

Emission and absorption spectra.

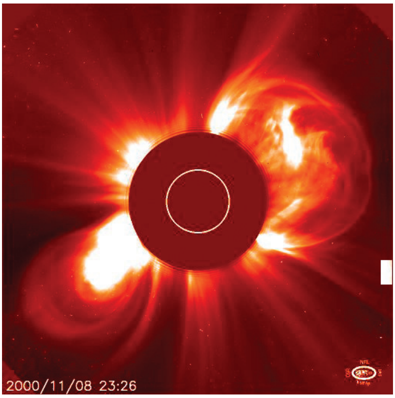
and that hydrogen can be used as a raw material for manufacturing all the heavier elements. This process is going on in the deep interiors of almost all stars including our own Sun. Most astronomers now believe that when our Milky Way system formed more than ten thousand million years ago, it consisted entirely, or almost entirely, of a mixture of hydrogen and helium, and that the present concentration of heavier elements has been built up from these raw materials over the intervening time.

While the absorption lines in stellar spectra can be used to determine the chemical composition of the star, not all spectral lines could be explained by laboratory experiments. In 1868, the English astronomer Sir Norman Lockyer, along with the French scientist Pierre Janssen, observed strong yellow lines in the solar spectrum which had never been seen in laboratory experiments. Lockyer deduced that they must be due to an unknown element, which he called helium, from the Greek *helios* (meaning Sun). Helium was not detected on Earth until 25 years later.

During the total solar eclipse of 7 August 1869 (which was visible from Alaska to North Carolina), emission lines (particularly a green line) were observed in the spectrum of the solar corona that did not correspond to any known spectral lines. Again it was proposed that these were due to an unknown element, provisionally named 'coronium'. But in 1920, the Indian physicist Meghnad Saha unravelled the mystery of the unknown lines. In a series papers published in the journal *Philosophical Magazine* and one in the *Proceedings of the Royal Society*, he demonstrated that these lines were due to highly ionised iron and nickel, the high ionisation being due to the extreme temperature of the solar corona.

The coronagraph

A total eclipse of the Sun provides astronomers a unique opportunity to study the solar corona, which otherwise remains invisible, hidden in dazzling light of the bright solar photosphere. But now astronomers do not have to wait for a total solar eclipse to study the corona. They can study the corona at any time using a device called the 'coronagraph'. The coronagraph was invented by the French astronomer Bernard Lyot in 1939, to enable astronomers to observe the corona surrounding from the Sun without having to wait for total solar eclipses. A coronagraph is a modified telescope that can see things very close to the Sun by blocking the Sun's bright photosphere



Coronagraph image of the Sun. The bright disc of the Sun has been artificially blocked to reveal the corona.

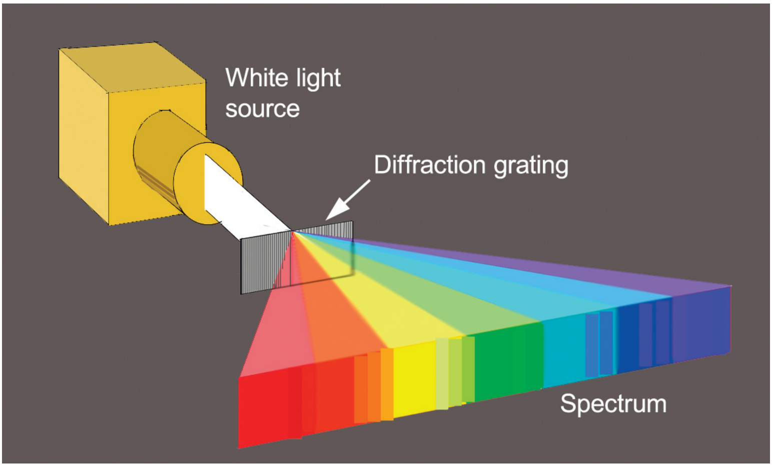
with a disc and revealing the faint solar corona, stars, planets and Sun grazing comets. In other words, a coronagraph produces an artificial solar eclipse.

Diffraction grating

While spectroscopy appeared to be a promising tool for the new science of astrophysics, early researchers in the field were limited by their equipment. Early spectrographs – such as those used by American doctor and astronomer Henry Draper – employed glass prisms to disperse the light. While simple in principle, prism spectrographs had a low resolution and it was often difficult to find a prism of sufficiently good optical quality.

While conducting his research on spectral lines, Fraunhofer had been using prisms to separate light into its component colours. However, it was also common practice to obtain a spectrum by passing the light through a very thin slit. It occurred to Fraunhofer that a wire mesh could be assembled in which the holes would act as hundreds of extremely thin slits, effectively splitting and re-splitting the passing light.

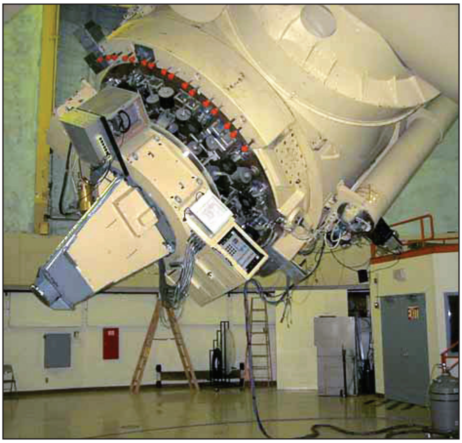
The principles of diffraction gratings were discovered by a Scottish mathematician and astronomer James Gregory, about a year after Newton's prism experiments, initially with artefacts such as bird feathers. The first man-made diffraction grating was made around 1785 by Philadelphia inventor David Rittenhouse, who strung hairs between two finely threaded screws. He was the first to use extensively the diffraction grating for spectral analysis. In 1821 Fraunhofer constructed a diffraction grating made up of 260 wires, producing a widely dispersed spectrum. He later found that an even wider (and more easily examined) dispersion could be obtained if the wires



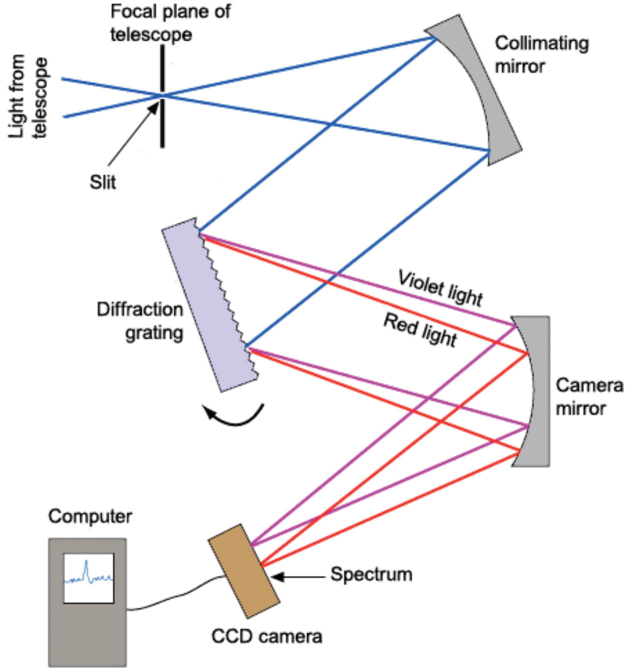
Production of spectrum by diffraction grating.

were set closer together. His work set the stage for the development of astronomical spectroscopy.

Modern diffraction gratings are usually made of glass or Perspex sheets on which thousands of narrow, closely spaced parallel grooves are ruled using special machines. In 1899, English scientist Henry Joseph Grayson designed a ruling machine to make diffraction gratings, which could make gratings with about 47,000 lines per centimetre. Ordinary CD and DVD media are every-day examples of diffraction gratings (reflecting type) and can be used to demonstrate the effect



A modern astronomical spectrograph can be a very large, complex instrument which is mounted at the focus of a telescope, as shown here.



Schematic drawing of an astronomical spectrograph.

by reflecting sunlight off them onto a white wall when a bright spectrum is seen.

Modern astronomical spectrographs can be very large, complex instruments. The spectrograph designed for the William Herschel 4.2-metre telescope at La Palma, Spain is about the size of a small car, but the optical components have to be kept in position to an accuracy of one thousandth of a millimetre.

Spectra and stellar classification

Early astronomical spectroscopy largely concentrated on the study of the Sun because it was bright and produced a bright spectrum. Later, however, astronomers began to turn their attention to the myriad other stars that dot the night sky. If we look at the spectrum of a star or galaxy, and see the lines characteristic of a particular element, then we can immediately say that element is present either in the star or galaxy itself or, in some special cases, in the space between a star and our telescope. This is important and exciting enough in itself, but so powerful are the techniques of spectroscopy that astronomers can do much more than just detect the presence of a chemical element or molecule.

Scientists like the English astronomer William Huggins and the Italian astronomer Angelo Secchi gathered as many spectra as possible and, like many scientists working in the 19th century, spent a considerable amount of time placing them into various classification schemes. Starting in 1863, Secchi began collecting the spectra of stars using a prism spectroscope and accumulated some 4,000 stellar spectrograms. Through analysis of this data, he discovered that the stars come in a limited number of distinct types and subtypes, which could be distinguished by their different spectral patterns. From this concept, he developed the first system of stellar classification: the four Secchi classes.

In 1885, American astronomer Edward C. Pickering at the Harvard College Observatory undertook an ambitious program of stellar spectral classification using spectra recorded on photographic plates. By 1890, a catalogue of over 10,000 stars had been prepared that grouped them into thirteen spectral types. By 1924, the American astronomer Annie Jump Cannon had expanded the catalogue to cover over a quarter of a million stars and developed a system of ten spectral types – O, B, A, F, G, K, M, R, N, S. (The mnemonic for remembering the sequence goes like this: "Oh Be A Fine Girl, Kiss Me Right Now, Sweetheart!") Subsequent measurements of the colours of stars showed

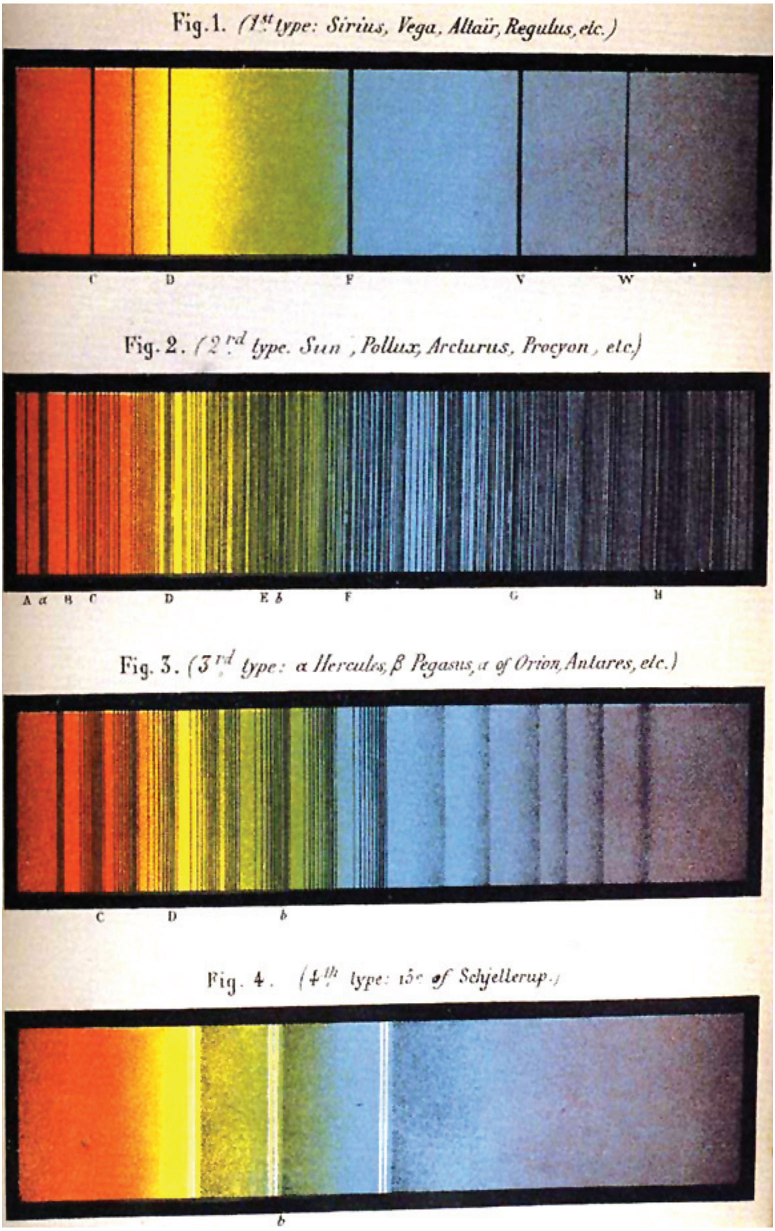


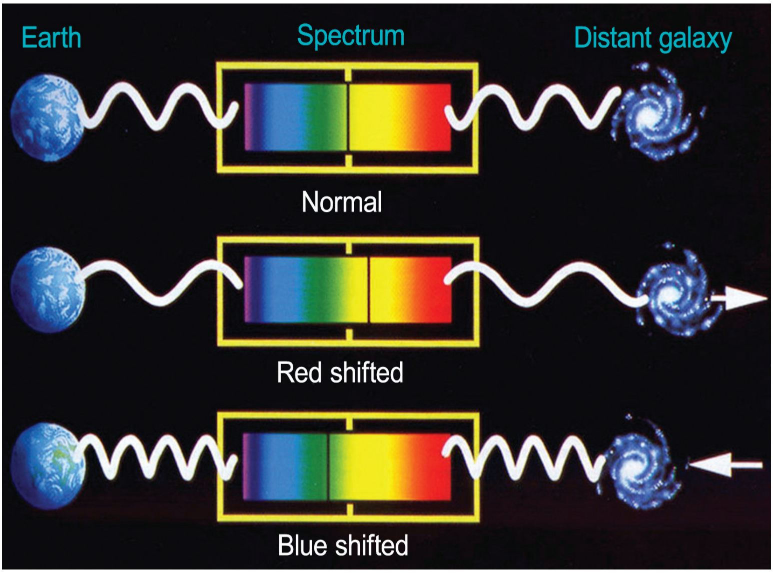
Fig. 1. (1st type: Sirius, Vega, Altaïr, Regulus, etc.)
C
D
F
V
W
Fig. 2. (2rd type. Sun, Pollux, Arcturus, Procyon, etc)
A
α
B
C
D
E
b
F
G
H
Fig. 3. (3rd type: α Hercules, β Pegasus, α of Orion, Antares, etc.)
C
D
b
Fig. 4. (4th type: 152 of Schjellerup.)
b

Secchi's four classes of stellar spectra, from a coloured lithograph in a book published around 1870.

that Cannon's sequence was also a colour sequence, ranging from blue to yellow and then to red. Almost at the same time, pioneering analyses of stellar spectra by other astrophysicists, prominent among whom were Arthur Eddington and James Jeans of England, together with the American, Henry Norris Russell, showed that the sequence of stellar spectra and colour could be attributed almost entirely to a variation in the temperature of the outer layer of the stars. Most stars are currently classified using the letters O, B, A, F, G, K and M, where O stars are the hottest, with temperatures of the order of 50,000° (Kelvin) and the letter sequence indicates successively cooler stars up to the coolest M class, with temperatures of about 3,000°. Our Sun is a yellow star belonging to the category G with a surface temperature of about 6,000°.

Spectra and the expanding Universe

The spectrograph has played a key role in our understanding of the Universe. The technique used is the measurement of the apparent shift in spectral lines when the source is moving. In 1842, the Austrian physicist Christian Doppler proposed that when a source of waves is moving relative to a stationary observer, there is a change in frequency of the waves received by the observer. This effect came to be known as 'Doppler Effect'. For sound, we experience it when a vehicle sounding a siren approaches, passes and moves away from us. The received frequency appears to increase (that is, the wavelength appears to shrink) during the approach, and then decrease (that is, the wavelength appears to stretch) as the vehicle moves away. Light waves, too, behave in a similar way. When an astronomical object is moving away from the observer its spectral lines shift towards the longer, red end of the spectrum – an effect known as 'red shift'. If the object is



Red shift explained. The wavelengths (colours) of light emitted by a moving astronomical object appear to shifts towards red when the object is fast moving away from the observer.

moving towards the observer its spectral lines would be shifted towards the shorter, blue end of the spectrum – an effect known as 'blue shift'.

By the first half of the 20th century big telescopes became available and it was possible for astronomers to examine the properties of faint galaxies, especially to record their spectra, which led to a astounding discovery. At that time, the prevailing view of the cosmos was that the Universe consisted entirely of the Milky Way galaxy. Using the 100-inch (2.5 m) Hooker Telescope at Mt. Wilson, the American astronomer Edwin Hubble identified Cepheid variables in several spiral galaxies, including the Andromeda galaxy. His observations, made during 1922-1923, proved conclusively that these galaxies were much too distant to be part of the

Milky Way and were, in fact, entire galaxies outside our own. This meant that the Universe was much larger than our Milky Way galaxy. In course of his observations of the spectra of distant galaxies, especially their red-shifts, Hubble discovered that except for a couple of galaxies including the Andromeda galaxy, all of them show large red shifts, meaning they were all moving away from us.

Another important discovery of Hubble was that the amount of red shift of a galaxy depended on its distance from Earth. In other words, the more distant the galaxy the larger was its red shift; that is, the faster it was moving away. Hubble calculated that for every million light-years of distance away from us, the velocity of a galaxy was increasing by 22 kilometres per second. This figure came to be known as Hubble's constant. The recession of galaxies provided the first indication that the Universe originated from a single point, in a Big Bang.

The measurement of red shifts also made it possible to determine the masses of different stars by the study of spectra of binary systems in which two gravitationally bound stars revolve around a common centre of gravity. By measuring the red shift in the spectrum of each star the velocities of the two stars of a binary system could be determined, from which the period of revolution and the circumference of the orbit and hence the size of the system could be determined. From these data, the mass of the two stars could be determined using Newton's theory. From such studies it has been possible to have an idea of the range of masses of stars, which varied from about one-tenth of the mass of the Sun to about 50 times a solar mass. It was also found that the lightest stars were the coolest and the heaviest were the hottest. Spectroscopy thus allowed astronomers to learn a lot about the stars that might not be possible otherwise.

Dark matter

Yet another remarkable discovery as a result of the study of red shifts of spectra of galaxies was the discovery of so-called 'dark matter'. While studying the red shifts of clusters of galaxies, the Swiss astrophysicist Fritz Zwicky found that most galaxies were moving much faster than seemed to be possible from what was known about the mass of the cluster. In 1933, he estimated the total amount of mass in a cluster of galaxies called the Coma Cluster, based on the motions of the galaxies near the edge of the cluster. When he compared this mass estimate to one based on the number of galaxies and total brightness of the cluster, he found that there ought to be about 400 times more mass than visible. The gravity of the visible galaxies in the cluster would be far too small for fast orbits he had detected, so something extra was required. This came to be known as the 'missing mass problem'. Based on these conclusions, Zwicky inferred that there must be some other form of matter existing in the cluster which has remained undetected and which provides enough of the mass and gravity to hold the cluster together. This missing mass is believed to make up what is known as 'dark matter'.

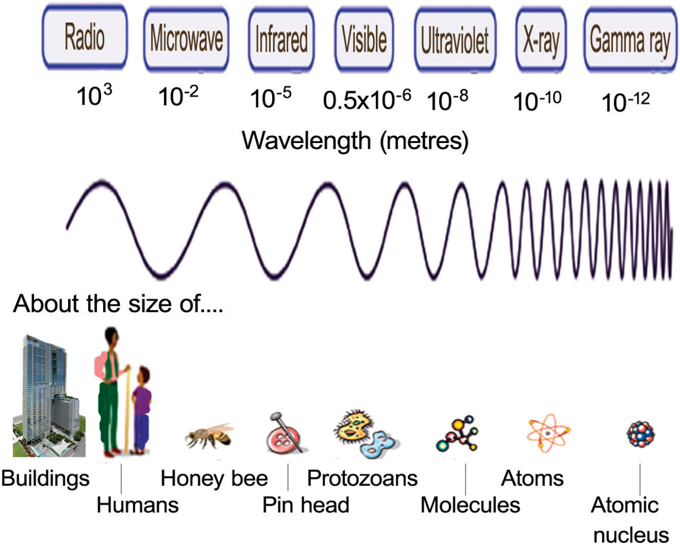
4

The invisible cosmos

Ever since Galileo turned his telescope skywards to look at the Moon and the planets four hundred years ago, astronomy has come a long way. Today astronomers not only study the sky in visible wavelengths using optical telescopes, they also look at cosmic objects in a wide range of wavelengths – from radio waves to gamma rays – not perceived by the human eye. The study of cosmos in these invisible wavelengths since the middle of the 20th century has yielded a wealth of surprising information about the Universe which lies beyond the range of optical telescopes.

The electromagnetic spectrum

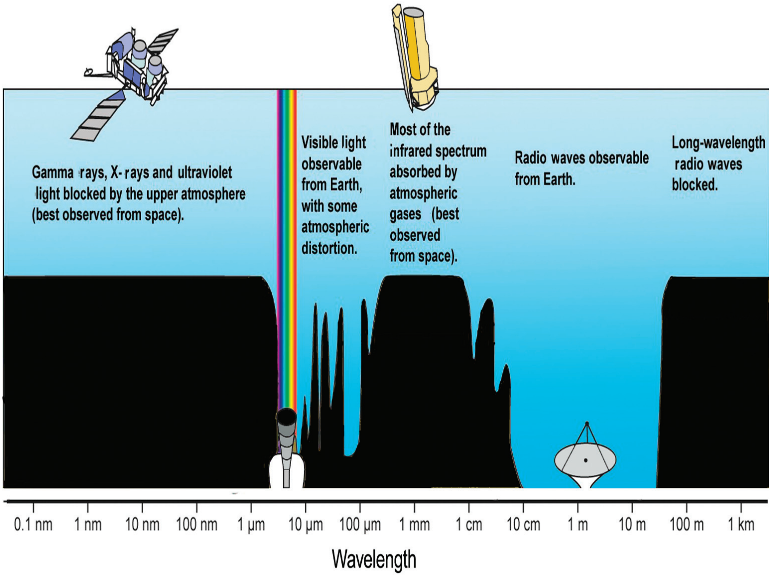
One of the most remarkable achievements of 19th century physics was presented in a paper titled "A Dynamical Theory of Electromagnetic Field" and a book *A Treatise on Electricity and Magnetism*. The author of both was a Scottish physicist James Clarke Maxwell. The paper appeared in 1865 and the book in 1873. Maxwell's work linked electricity and magnetism to the properties of light, which he considered as 'waves' created by oscillations of electrical and magnetic fields. Maxwell called these waves 'electromagnetic radiation' and suggested that such radiation might also be found at wavelengths longer as well as shorter than that of visible light. By the end of the 1880s the German physicist Heinrich Hertz through a series of brilliant experiments had discovered 'radio waves', which could be reflected and refracted but had a wavelength millions of times longer than visible light.



The electromagnetic spectrum

As we know today, visible light is a form of electromagnetic radiation and makes up only a very small part of the electromagnetic spectrum. The human eye is sensitive to only this limited range of wavelengths – corresponding to the colours red to violet. Our eyes cannot perceive radiation outside this range, which comprises the whole range of wavelengths from infrared to radio waves beyond red, and from ultraviolet to gamma rays beyond violet. The difference between visible light and the rest of the electromagnetic spectrum lies only in their wavelengths (or frequencies). Radio waves have relatively longer wavelengths while gamma rays have much shorter wavelengths compared to visible light.

The electromagnetic spectrum is a vast band of energy frequencies extending from radio waves to gamma rays – from the very lowest frequencies (i.e., longest wavelengths) to the highest possible frequencies (i.e., shortest


Gamma rays, X- rays and ultraviolet light blocked by the upper atmosphere (best observed from space).
Visible light observable from Earth, with some atmospheric distortion.
Most of the infrared spectrum absorbed by atmospheric gases (best observed from space).
Radio waves observable from Earth.
Long-wavelength radio waves blocked.
0.1 nm
1 nm
10 nm
100 nm
1 μm
10 μm
100 μm
1 mm
1 cm
10 cm
1 m
10 m
100 m
1 km
Wavelength

Atmospheric penetration of electromagnetic waves.

wavelengths). The spectrum includes radio (long, short, and medium waves, and microwaves), infrared, visible light, ultraviolet, X-rays, and gamma rays – which have the shortest wavelengths. In other words, radio waves have photons with low energies, microwaves have a little more energy than radio waves, infrared has still more, then visible, ultraviolet, and X-rays; gamma-rays have the most energetic photons. Just as our eyes can perceive visible light, as do photographic film and CCDs, different kinds of detectors are needed for detecting each type of electromagnetic radiation. Although radio waves reach the ground from space, the Earth's atmosphere is opaque to a large part of the electromagnetic spectrum including some infrared and most ultraviolet wavelengths, and X-rays and gamma rays, which do not reach the ground. So astronomical observations at these wavelengths cannot be done from Earth-based observatories.

The radio Universe

Radio waves were first produced and detected by Heinrich Hertz in 1880s in Germany. In 1895, the Indian physicist Jagadis Chandra Bose for the first time produced microwaves in the laboratory and demonstrated wireless communication. Subsequently, in 1901, the Italian electrical engineer Guglielmo Marconi successfully transmitted radio signals across the Atlantic, heralding a new era in long-distance communication. Both Bose and Marconi used special detectors to receive the transmitted radio signals.

Radio waves that we receive in our radio sets at home or in the car are broadcast from transmitting antennas at the radio station. A smaller antenna built in the receiving set or the car antenna picks up the signals, which are then converted into sound by the electronic circuit of the receiving set. Television also works in a similar way, but here the wavelength of the radio waves used is of the order of a few centimetres called microwaves.

But transmitters at radio or TV stations are not the only sources of radio waves. We now know that radio waves are also emitted by other things outside our Earth – such as stars, galaxies and gases in space. By studying the radio waves coming from space we can learn a lot about what the Universe is made of. But we cannot see radio waves and so cannot observe in radio wavelengths using optical telescopes. Special kinds of telescopes called radio telescopes are needed for studying the Universe in radio wavelengths.

The infrared Universe

Radio waves are the longest of the electromagnetic waves. Next comes infrared. Interestingly, although Newton had produced the first spectrum by passing sunlight through a glass prism in the 1660s, physicists did not know about infrared radiation at that time. It was the German astronomer William Herschel who discovered infrared radiation in 1800.

Herschel was interested in learning how much heat passed through the different colour filters he used to observe the Sun and noticed that filters of different colours seemed to pass different levels of heat. Herschel thought that the colours themselves might contain different levels of heat, so he devised a clever experiment to investigate his hypothesis. He directed sunlight through a glass prism to create a spectrum and measured the temperature of each colour in the spectrum. He used three thermometers with blackened bulbs (to better absorb the heat) and placed one bulb in each colour while the other two were placed beyond the spectrum as control samples. As he measured the temperatures of the violet, blue, green, yellow, orange and red light, he noticed that all of the colours had temperatures higher than the controls and that the temperature of the colours increased from the violet to the red part of the spectrum. After noticing this pattern, Herschel decided to measure the temperature just beyond the red portion of the spectrum in a region where there was no sunlight. To his surprise, he found that this region had the highest temperature of all.

Herschel performed further experiments on the invisible rays that existed beyond the red part of the spectrum and found that they were reflected, refracted, absorbed and transmitted just like visible light. What Herschel had discovered was a form of radiation beyond red light. These rays were later named infrared rays or infrared radiation (*infra* means 'below'). Herschel's experiment was important not only because it led to the discovery of infrared radiation, but also because it was the first time that someone showed that there were forms of light that we cannot see with our eyes.

Infrared radiation is a ubiquitous form of invisible electromagnetic radiation that is present almost everywhere. In fact, all objects above the temperature of zero degrees absolute (minus 273.16°C) give off infrared radiation. We can feel infrared radiation as heat when it falls on our skin. Many night vision devices used by the army to locate the enemy in darkness work by detecting the infrared radiation given off by the human body.

But astronomers are interested in infrared radiation for another reason. The study of the sky at infrared wavelengths can reveal the location and character of 'cool' material in the cosmos – material that is not hot enough to give off light – such as clouds of gas and dust in the process of forming stars or planets, or a star near the end of its life. On Earth, infrared radiation is commonly associated with 'warm' objects, but celestial objects that emit in these wavelengths are actually a great deal cooler than objects that emit visible light. For example, very young stars, which may not be visible in optical telescopes, are very bright infrared emitters. Besides, the longer wavelength allows infrared radiation to penetrate cosmic dust found around or between stars and galaxies, which are opaque to much shorter visible wavelengths, thus allowing astronomers to look behind impenetrable clouds of cosmic dust.

The wavelength of infrared radiation ranges from a few microns to a few hundred microns (one micron is one millionth of a metre). In fact, infrared radiation is longer than red light but shorter than microwaves. Although Herschel used thermometers to detect infrared radiation in the solar spectrum, much more sensitive and reliable detectors are available today for precision measurement of the incident radiation, especially in astronomy.

An infrared detector is basically a photodetector that responds to infrared radiation. The two main types of detectors are thermal and photonic. The thermal (heating) effects of the incident infrared radiation are used in detectors that utilise temperature-dependent phenomena. A bolometer is based on change in resistance and is used for measuring infrared radiation or any other form of radiant energy. It was invented in 1860 by the American astronomer Samuel Pierpont Langley. Bolometers are now primarily used for the detection of heat energy transmitted from distant sources such as stars and galaxies and interstellar dust.

Thermocouples and thermopiles use the thermoelectric effect in which a potential difference is generated due to a difference in temperature. In infrared spectrometers the pyroelectric (having or using the property of becoming electrically charged when heated) detectors are the most widespread. Photonic detectors use semiconductors in which incident infrared photons can cause electronic excitations. In photoconductive detectors, the resistivity of the detector element is monitored. But to achieve best sensitivity and cut down thermal noise infrared detectors need to be cooled to very low temperatures.

Near-infrared radiation (with wavelengths close to that of visible light) behaves in a very similar way to visible light and can be detected using similar electronic devices. For this reason, the near-infrared region of the spectrum is commonly incorporated as part of the 'optical' spectrum (most scientific instruments such as optical telescopes cover the near-infrared as well as the visible). The far-infrared extends to sub-millimetre wavelengths, which are observed by telescopes such as the James Clerk Maxwell Telescope at Mauna Kea Observatory in Hawaii.

The main limitation that comes in the way of doing infrared astronomy using ground-based telescopes is the water vapour in the Earth's atmosphere, which absorbs a significant amount of infrared radiation of wavelengths longer than a few micrometres. Most of the infrared radiation coming to us from space is absorbed by water vapour and carbon dioxide in the Earth's atmosphere. Only in a few narrow wavelength ranges, can infrared light make it through (at least partially) the atmosphere to a ground based infrared telescope.

The Earth's atmosphere causes another problem for infrared astronomers; the atmosphere itself radiates strongly in the infrared, often emitting more infrared radiation than the object in space being observed. This atmospheric infrared emission is highest at a wavelength of about 10 microns. So the best views of the infrared Universe from ground based telescopes are at infrared wavelengths which can pass through the Earth's atmosphere and at which the atmosphere does not radiate. For this reason ground based infrared observatories are usually placed near the summit of high, dry mountains to get above as much of the atmosphere as possible. But most infrared observations are done using space-based telescopes.

All of the planets and moons in our solar system emit strongly in the infrared. This infrared emission is the heat from their atmospheres and surfaces which peaks in the mid to far infrared (15 to 100 microns) and can be observed only from space. Solar system objects also reflect infrared radiation from the Sun. This reflected radiation peaks in the near infrared at about 0.5 microns that can be received on ground. The study of the infrared radiation from solar system objects has given us much information about their composition. For planets and moons which have atmospheres, infrared studies can show us how the abundance and composition of atmospheric gases as well as the temperature of the atmosphere vary with depth. In addition, infrared astronomy has led to the discovery of new comets and asteroids and bands of dust which lie in our solar system.

Watching star formation

Many of the most interesting infrared objects in the sky are associated with star formation. Stars form from collapsing clouds of gas and dust. As the cloud collapses, its density and temperature increase. The temperature and density are highest at the centre of the cloud, where a new star will eventually form. The object that is formed at the centre of the collapsing cloud is called a protostar that ultimately becomes a star. Since a protostar is embedded in a cloud of gas and dust, it is difficult to detect in visible light. Any visible light that it does emit is absorbed by the material surrounding it and causes the dust to warm up and radiate in the infrared. Infrared studies of star forming regions can give astronomers important information about how stars are born and thus on how our own Sun and solar system were formed.

In the 1980's, astronomers using data sent back by the *IRAS* satellite discovered about two dozen stars which had infrared-emitting dust surrounding them, extending hundreds of astronomical units from the stars. This discovery inspired astronomers to make more detailed observations of these stars. What they found around these stars were flat, disk-shaped, areas of dust in which planets have formed or could be forming. These findings have led the way to one of the most exciting new areas of research in astronomy – the search for planets around other stars.

Another strong emitter of infrared radiation in space is the interstellar matter that exists between the stars. Most of this gas and dust originates from the death of stars which either exploded (supernova) or blew off their outer layers, returning their material to interstellar space. From this material, new stars are formed. In fact our Sun and the solar system were formed from such interstellar matter. Often, the gas and dust between the stars can be detected only in the infrared. By using infrared detectors, astronomers can penetrate the often invisible interstellar gas and dust clouds and gain much information about their composition and structure. Infrared astronomy has also resulted in the detection of several types of complex interstellar molecules.

Infrared astronomy, both from ground and from space thus not only allows astronomers to discover new objects and view previously unseen areas of the Universe, but it can also add to what is already known about visible objects.

Beyond violet

Ultraviolet radiation is electromagnetic radiation with wavelengths shorter than those of visible light but longer than X-rays. The discovery of ultraviolet radiation was intimately associated with the observation that silver salts darken when exposed to sunlight. In 1801 the German physicist Johann Wilhelm Ritter made the noteworthy observation that invisible rays just beyond the violet end of the visible spectrum were especially effective at darkening silver chloride-soaked paper. He called them 'de-oxidizing rays' to emphasise their chemical reactivity and to distinguish them from 'heat rays' at the other end of the visible spectrum. The simpler term 'chemical rays' was adopted shortly thereafter, and it remained popular throughout the 19th century. The term chemical rays was eventually dropped in favour of ultraviolet radiation.

Astronomers had known that high-energy processes, especially very high temperatures in cosmic bodies release copious amounts ultraviolet radiation. For example, our Sun releases plentiful amounts of ultraviolet radiation, but most of it is absorbed in the upper atmosphere by the Earth's ozone layer. Interstellar gas at temperatures close to 1,000,000°C is also quite prominent in the ultraviolet. So studies in ultraviolet wavelengths could provide new insights into cosmic processes in the Sun and certain other stellar objects, such as white dwarfs. Ultraviolet studies can also provide valuable information about chemical abundances in space.

Ultraviolet detectors generally use either a solid-state device, such as one based on silicon carbide or aluminium nitride, or a gas-filled tube as the sensing element. Ultraviolet sensors for astronomy have requirements distinct from those meant for industrial or military applications. First, they have to be insensitive to light at optical wavelengths, because astronomical objects (for example, the Sun) often emit much more (10^4-10^8) visible photons for every ultraviolet photon. Ultraviolet detectors using gallium nitride, aluminium nitride, and their alloys offer significant potential for solar-blind ultraviolet detectors capable of operating at high temperatures and in hostile environments.

The sky in X-rays

In 1895, the German physicist Wilhelm Conrad Röntgen, while experimenting with vacuum tubes accidentally discovered X-rays. A week later, he took an X-ray photograph of his wife's hand which clearly revealed her wedding ring and her bones. The photograph electrified the general public and aroused great scientific interest in the new form of radiation. Röntgen called it 'X-ray' to indicate it was an unknown type of radiation.

Like infrared and ultraviolet radiation, X-rays are also not visible to the human eye. But they can be detected and recorded on photographic film. Now techniques are available for converting X-rays into visual images or into electronic signals that can be recorded. In medical science, X-rays are used only as a diagnostic tool, for imaging internal organs of the human body. In an X-ray machine, X-rays are produced using extremely high-voltage electricity. So, nobody could possibly imagine that X-rays could also come from space. But it is now a fact.

However, observation of the sky at X-ray wavelengths from ground is almost impossible. This is because, although the more energetic X-rays can penetrate the air for distances of at least a few metres, the Earth's atmosphere is so thick that virtually no X-rays from outer space are able to reach the Earth's surface. X-rays in the energy range where most celestial sources give off the bulk of their energy can be stopped by a few sheets of paper. So to observe X-rays from the sky, the X-ray detectors must be flown above most of the Earth's atmosphere.

Unlike optical astronomy, the earliest records of which go back to several centuries, the history of X-ray astronomy is just over six decades old. Before the invention of rockets, it was impossible to detect X-ray emissions coming from celestial objects from ground, as these radiations are totally cut-off by the Earth's atmosphere. The first X-ray pictures of the sky were taken in 1947, just after the end of the Second World War when the Americans launched a captured German V-2 rocket to a height of 160 km. The rocket carried an X-ray camera, which took 'pictures' of the Sun. The first pictures were not spectacular, but they did show that the Sun does emit some X-rays. The X-ray picture of the Sun showed the regions in the Sun's very thin outermost layer called corona, which are extremely hot and emit X-rays. Later observations from the American orbiting space station *Skylab* showed the X-ray sources to be associated with other high-activity areas on the Sun, such as sunspots and solar flares.

(It must be mentioned here that an X-ray picture of the Sun or any other astronomical object has no resemblance to the kind of X-ray shadow pictures we get of the human body in a hospital. In medical X-ray the image is formed by the shadow of dense materials such as bones, but in astronomy the sources emitting X-rays show up as bright spots or areas.)

Apart from the Sun, other sources of X-rays were subsequently discovered in space. Extremely hot gases in galaxies and star clusters are also known to give off X-rays, as do remnants of supernova explosions. Another copious source of cosmic X-rays are binary stars in which one of the components is a white dwarf, a neutron star, or even a black hole. All these sources emit X-rays by extreme acceleration of electrons – a process known as 'synchrotron' radiation (so called because this kind of radiation was first discovered in a high-energy particle accelerator called synchrotron). It was discovered that, when electrons are accelerated to very high speeds in a strong magnetic field, they emit radiation. The wavelength of this radiation depends on the speed of the electrons; the faster they move the shorter the wavelength becomes. If the speed is very high, the wavelength of the emitted radiation falls in the X-ray region.

After a massive star explodes as a supernova at the end of its life, electrons in the hot exploding gas also move through strong magnetic field at high speed, which leads to emission of X-rays. When a binary star has a white dwarf or a neutron star as one of the pair, and if the two are close enough, then the smaller, denser companion attracts material from the larger companion. As the gaseous material moves over to the very dense star, it suddenly becomes heated strongly enough to emit X-rays. In such cases the heating is sudden and intense, but does not last for long. These X-ray sources, therefore, flare up in less than a second and then fade out in a matter of minutes. If one component of the binary is a black hole, then gas and electrons stream into it from its companion star at extremely high speed. The material swirls very fast round the hole before falling in, leading to the emission of X-rays as synchrotron radiation. In fact, emission of synchrotron X-rays offer an easy way of detecting black holes, which are invisible, as no light can come out of them.

Since the coming of rockets and satellites, there has been rapid growth in X-ray astronomy. The detection of cosmic X-ray sources has provided evidence of the kind of energetic processes going on in the far reaches of the cosmos.

The gamma-ray Universe

As we have seen, the cosmos, when glimpsed through different bands of the electromagnetic spectrum, presents many contrasting views. And of all of them the view at gamma-ray wavelengths may be the most exciting. Since gamma rays are the most energetic of the electromagnetic radiations, they provide an insight into the most violent, chaotic, and explosive processes going on in far reaches of the Universe. Gamma-ray astronomy provides a unique view of the hottest, most energetic regions of the cosmos.

Gamma rays were named by the British physicist Ernest Rutherford in 1903. They are the most energetic among the three kinds of radiation given off by radioactive elements. Long before experiments could detect gamma rays emitted by cosmic sources, scientists had known that the Universe should be producing these photons. Work by American physicists Eugene Feenberg, Henry Primakoff, Philip Morrison and others had led scientists to believe that several processes occurring in the Universe would result in gamma-ray emission. These processes included cosmic ray interactions with interstellar gas, supernova explosions, and interactions of energetic electrons with magnetic fields. But it was not until the 1960s that means were available to actually detect these emissions from space. Gamma rays are studied with sophisticated pinhole cameras, or stacks of scintillators that produce brief flashes of light when hit by high-energy photon.

In space, gamma rays are produced by violent processes taking place in the interior of galaxies. For example, gamma rays are produced when lighter elements are created by nuclear fusion in the interior of stars; and also in supernova explosions, where heavier elements are created. Gamma rays are also produced in processes involving the interaction of matter and antimatter and of subatomic particles with other particles or with magnetic fields, matter or even photons. Many of these processes are believed to occur in the extreme conditions found in and around supernovas, black holes, pulsars and quasars. Although gamma rays are a highly penetrating form of radiation, they are readily absorbed in the Earth's thick atmosphere. So, ground based observation is almost impossible, and observations have to be made from space.

Interestingly, the detection of gamma rays from space came about almost accidentally. In the late 1970s the United States had been launching Earth satellites to detect gamma-ray emissions from nuclear testing. Surprisingly, these satellites instead discovered bursts of gamma rays coming from deep space. These occurred at a rate of one or two per day and typically lasted for a few seconds to a few minutes. But their source remained a mystery. Since then several other spacecraft have been launched to probe gamma rays coming from space. Later studies showed that the powerful gamma ray bursts come from the merger of two neutron stars. Theoretical calculations show that in the final seconds of such a merger the brightness of the two stars together can exceed that of a thousand million galaxies like the Milky Way before they end up in the formation of a black hole.

5

The radio sky

Before 1931, to study astronomy meant to study the objects visible in the night sky. Indeed, most people probably still think that's what astronomers do – wait until dark and look at the sky using their naked eyes, binoculars, and optical telescopes, small and large. Before 1931, we had no idea that there was any other way to observe the Universe beyond our atmosphere.

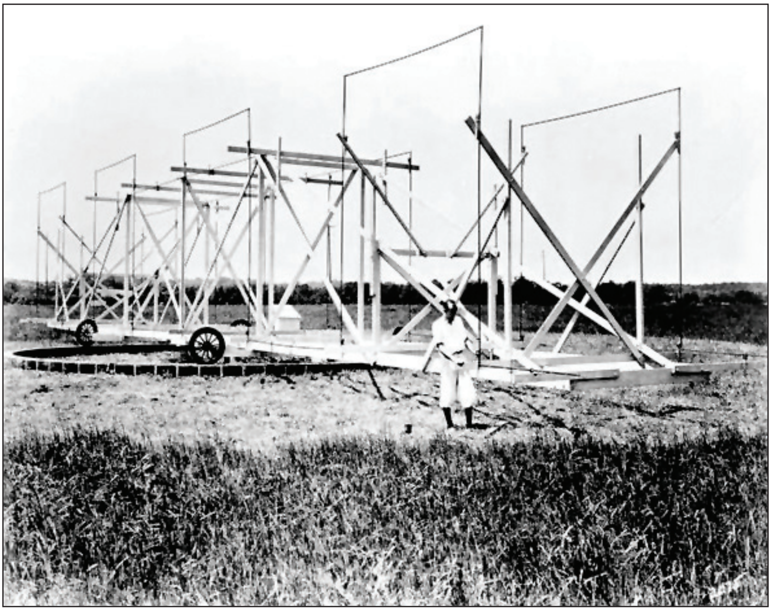
In science, new discoveries are often made by chance, only because of the sheer inquisitiveness of a few individuals who refuse to give up. A remarkable breakthrough in the way we observe the Universe also came about in the same manner in the 1930s, and radio astronomy was born. With that discovery, astronomers had yet another window through which they could observe the cosmos, and the view turned out to be astounding. Strange cosmic objects and violent processes going on in the far reaches of the cosmos could be observed for the first time.

Radio waves from space

By the beginning of 20th century, radio transmitters and receivers had become available. The First World War stimulated the development of radio, and in the 1920s there was an explosive development of radio broadcasting. We know that radio waves can only be received using special antennas. In fact, all radio receivers (even mobile phones with radio) work by receiving radio waves using an antenna and then separating the sound signal and amplifying it using an electronic circuit. But the signals that we receive in our radio sets or mobile phones are sent out by transmitters on Earth. Till early 1930s nobody could imagine that radio signals could also come from outer space.

If the human eye could see in radio wavelengths, the Universe would appear quite different from what optical telescopes reveal. The first source of radio waves from space was discovered in December 1931, during a routine study of static noise in radio transmissions, which is a common phenomenon and adversely affects the quality of the signals received. It was a time when a lot of studies were going on to find out better methods of radio communication. In the 1920s, amateur (ham) radio operators across the world were establishing communication links among themselves using short-wave frequencies. Their experience showed that short-wave radio links could be used to carry intercontinental telephone calls, which might save the expense of laying undersea cables. But soon, such wireless telephone links were found to be plagued by atmospheric static noise caused by lightning and other atmospheric disturbances, which badly affected transmission quality.

It was at this time that a young radio engineer named Karl Jansky, working with the AT&T Bell Labs in New Jersey, USA, was assigned the task of identifying the origins of the unwanted short-wave noise. He assembled a high-quality receiver and antenna designed to work at short wavelengths, specifically at wavelength of 15 metres, which was being used for ship-to-shore communication. The antenna was built us as an array of separate aerials mounted on a frame 30 metres long and four metres high. The array was set on wheels so that it could be rotated to see if the static noise varied in strength as the antenna was pointed in different directions.



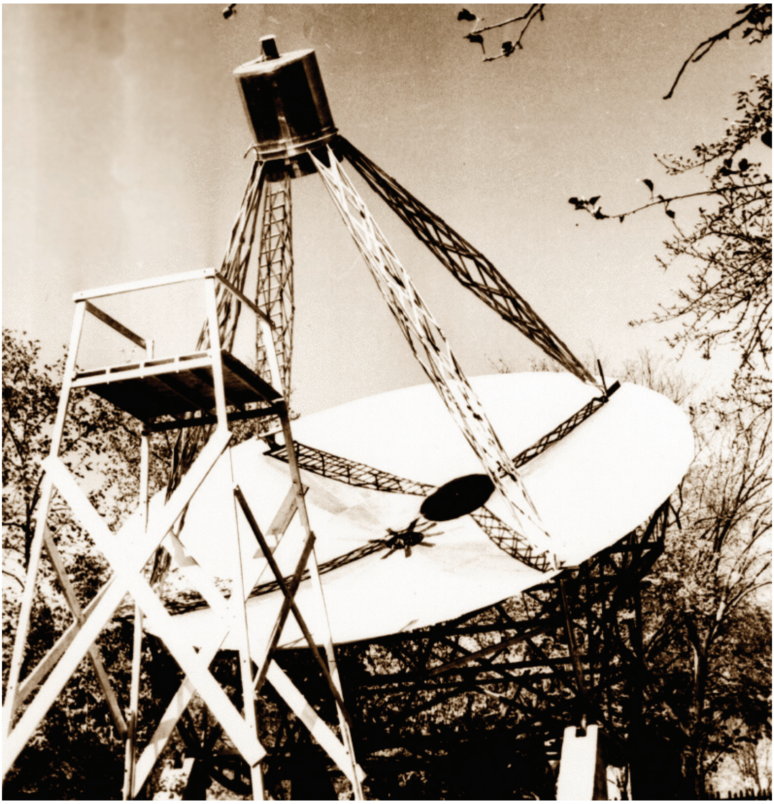
Karl Jansky's radio antenna consisted of an array of separate aerials mounted on a steerable frame 30 metres long and four metres high.

Using his antenna, Jansky found that most of the noise was due to thunderstorms and other terrestrial causes. (Thunderstorms generate strong radio signals that produce the sharp crackling noise heard in medium-wave and short-wave radio broadcasts.) However, there was one source of a constant hiss for which no terrestrial source could be identified and which seemed to move from east to west in course of the day. As his antenna rotated, he found that the direction from which this unknown static originated changed gradually, going through almost a complete circle in 24 hours. No astronomer himself, it took him a while to surmise that the static must be of extraterrestrial origin, since it seemed to be correlated with the rotation of Earth. He at first thought the source was the Sun. However, he observed that the radiation peaked about 4 minutes earlier each day. He knew that the rotation period of Earth with respect to the stars (known to astronomers as a sidereal day) is about 4 minutes shorter than a solar day (the rotation period of Earth with respect to the Sun). Jansky therefore concluded that the source of this radiation must be much farther away than the Sun. With further investigation, he was convinced that the radio waves were coming from a particular direction in the sky, from the direction of the constellation of Sagittarius and the source was probably the centre of the Milky Way. He made this discovery in 1932 and announced his findings in 1933. His announcement was reported on the front page of the *New York Times* on 5 May 1933.

Jansky's discovery of radio waves coming from space was a real scoop, but surprisingly, it did not attract the attention of astronomers immediately. No one seems to have immediately realised the tremendous potential of the new discovery in extending the limits of astronomy. To most professional astronomers, Jansky's discovery was a mere curiosity, and they did not follow up on it.

After two years of total neglect, the nascent science of radio astronomy was rescued from oblivion by an enthusiastic amateur who took notice of Jansky's discovery. Grote Reber was a radio engineer and an avid ham operator in Wheaton, Illinois, USA. Reber had spent much time making long-distance contacts on the amateur short-wave bands. He had "worked" all continents and 60 foreign countries. In those days, that was quite an achievement, and it left Reber thinking, as he later wrote, "there were no more worlds to conquer." When he read of Jansky's discovery, he realised that he had still a long way to go. But he did not want to repeat Jansky's experiment; rather decided to design his own antenna.

Reber's first assumption was that radio waves, like those of visible light, would be emitted by the hot stars forming



Grote Reber's original radio telescope was almost 10 metres in diameter and was built of wood with a galvanised iron sheet layer for the dish.

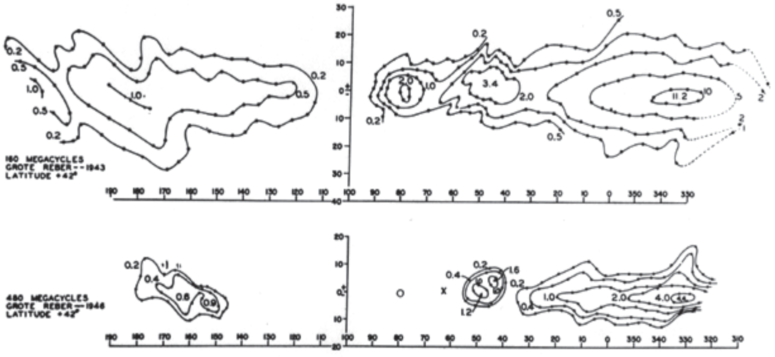
the Milky Way. And if that were so, then most of the radio energy from the stars would be at shorter wavelengths than Jansky's antenna could detect. He also knew that each tenfold decrease in wavelength would raise the power by a factor of hundred. Working at shorter wavelengths would also allow much more accurate position measurement.

In 1937, Reber decided to build his first radio telescope. In his spare time, with his own resources, he built for himself a steerable parabolic dish antenna (like the ones cable operators use to receive TV signals from satellites) in his backyard to scan the sky for radio signals. Reber's antenna was quite large, almost 10 metres in diameter and was built of wood with a galvanised iron sheet layer for the dish. Since it was designed to receive radio waves of only 9-centimetre wavelength, it required the reflecting surface to be accurate to only about a centimetre to give essentially perfect performance. (In comparison, the mirror of a reflecting optical telescope would need to be polished to an accuracy of 0.5 microns.) Reber completed the telescope in four months. In an era when nobody had even dreamt of artificial satellites and television had not yet emerged from the laboratory, this antenna became a public curiosity, drawing amazed remarks from his neighbours.

But Reber's enterprise produced rich dividends. He hooked up his massive dish antenna to a sensitive radio receiver to make some remarkable recordings of cosmic radio waves. Using his set-up, Reber was able to precisely pinpoint the direction from which the radio signals earlier detected by Jansky were coming. It was indeed coming from the direction of the centre of our Milky Way galaxy.

Radio telescopes

In principle a radio telescope is the same as an optical reflecting telescope. The antenna of a radio telescope is essentially a parabolic surface is covered with a thin sheet of metal or wire mesh, depending on the wavelength to be received, which reflects the radio waves to a focus. A short wire aerial (dipole) is fixed at the focus of the parabolic dish to collect the radio waves and convert it to a voltage that can be amplified. A radio receiver amplifies these signals and records their strength at different frequencies and from different directions. The information is analysed by a



Reber's radio frequency map of the sky published in 1944.

computer to draw a picture of the source of the radio waves or to analyse the chemicals found in the source.

The output from a radio telescope is usually in the shape of a contour 'map' outlining the areas of similar signal strength. (Modern radio telescopes use computers to produce false-colour images of the radio sky.) Reber continued his investigations during the early 1940s and in 1944 published the first radio frequency sky maps. His observations produced an amazing view of the Universe. His radio 'maps' showed for the first time the startling differences between the 'visible' sky and the 'radio' sky. It marked the dawn of an entirely new branch of astronomy, which came to be known as 'radio astronomy'. Until the end of World War II, Reber was the lone radio astronomer in the world.

Around the same time that Reber published his results, developments were taking place in the field of highly sensitive shortwave receivers for use in radars. The increased positional accuracy obtained with short wavelengths was found to apply to radar echoes as well as to radio astronomy.

The Second World War saw tremendous strides in shortwave techniques and around that time the British Army assigned English physicist James Stanley Hey the task of studying German radar jamming techniques. In course of his investigation Hey made a surprising discovery; he found that the jamming of British anti-aircraft radar installations spread over most of the country was not being caused by the Germans but by an extraneous source of radio noise. Further he found that the source moved during the day. Ultimately the source of the radio noise turned out to be the Sun and not a new and powerful enemy transmitter. On further investigation Hey discovered it was a large sunspot near the centre of the Sun's disc that was acting as a powerful shortwave radio source.

Hey's discovery of radiation from active regions on the Sun was accidental. Then, in June 1942, while testing a new microwave receiver, working at 3.2 centimetres, G.C. Southworth of Bell Telephone Laboratories detected strong signals from the Sun. Unlike the signals detected by Hey from the active region of sunspot, the signal received by Southworth using his microwave receiver was steady in intensity and was believed to be due to the high temperature of the Sun.

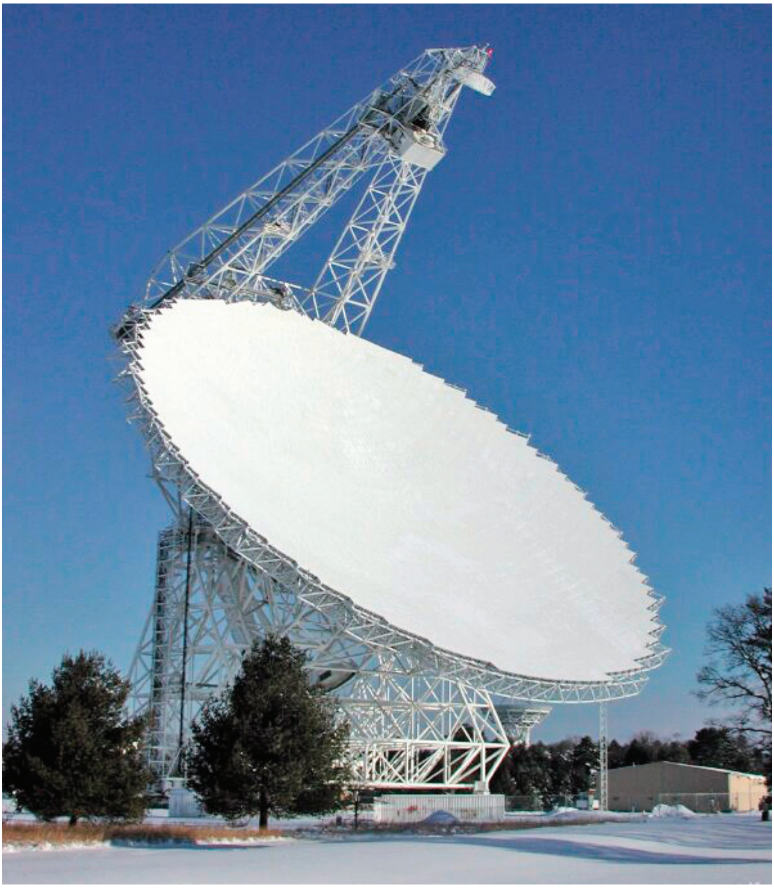
After the war, radio astronomy developed rapidly, and has today become of vital importance in our observation and study of the Universe. Some of the earliest major initiatives in the post-war development of radio astronomy came from scientists who had worked on the British radar programme, notably Bernard Lovell at the Jodrell Bank and Martin Ryle at Cambridge. After the war the radar equipment were rapidly turned to peaceful use. Complete radar systems were used in radar astronomy, bouncing radio signals off astronomical bodies and detecting the echoes. In January 1946, J.H. De Witt of the US Army Signal Corps

Laboratory succeeded in detecting radar echoes from Moon, almost 4,00,000 kilometres away. He was able to measure the 2.5-second delay sufficiently accurately to determine the Earth-Moon distance with a precision of about 1,500 kilometres. This was the first direct measurement of the distance between two bodies in the solar system.

As radio astronomy became an established scientific discipline, radio telescopes with large dish antennas became the most powerful tool in the hands of radio astronomers. The first really large fully steerable radio telescope was completed in 1957 at Jodrell Bank, England. This telescope with a dish diameter of 76 metres is still used for a number of research programmes.

The most technically advanced steerable single-dish radio telescope in the world today is the Robert C. Byrd Green Bank Telescope (GBT). Located at the National Radio Astronomy Observatory (NRAO) site at Green Bank, West Virginia, USA, the GBT is also the world's largest land-based movable structure. Its 110-metre by 100-metre dish boasts more than 8,000 square metres of area for collecting faint radio waves from space. The reflecting surface of the GBT is composed of 2,004 metal panels, each of which can be controlled independently. Unlike conventional radio telescopes, which have a series of supports in the middle of the surface, the GBT's dish is unblocked, so incoming radiation meets the surface directly. This design increases the useful area of the telescope and eliminates reflection and diffraction that ordinarily complicate a radio telescope's pattern of response.

The Green Bank Telescope is also incredibly precise. It can be pointed with an accuracy of one arc second – equivalent to the width of a single human hair seen about two metres away. That precision has enabled the



The Green Bank telescope at Green Bank, West Virginia, USA is the most technically advanced steerable single-dish radio telescope in the world today.

astronomers to measure the magnetic field of a single galaxy from the faint radiation that travelled many thousands of millions of years.

Completed in 2000, the GBT is a leader in the scientific study of pulsars - dense neutron stars that serve as laboratories in which astronomers study the physics of extreme states of matter and enormous magnetic fields. The

The Arecibo radio telescope is the largest single dish radio telescope in the world with a 305-metre fixed spherical reflector built in a large natural depression on a mountainside.

GBT can also detect the fingerprints of atoms and molecules far into the depths of the Universe, yielding new knowledge about star formation, the structure and motions of gas in galaxies, and Nature's fundamental constants.

The largest single dish radio telescope in the world is the 305-metre fixed spherical reflector operated by Cornell University near Arecibo in Puerto Rico. The 305-metre antenna, built in a large natural depression on a mountainside, has an enormous collecting area, but the beam can be moved through only a limited angle of about 20° from the zenith. The advent of faster computers has greatly helped in not only processing the data collected by the large dish antennas but also steering them as well.

Radio interferometry

Since radio waves are much longer than light waves, radio telescopes need large receiving antennas. For the same reason the resolution of radio telescopes is also limited. Radio astronomers therefore use an innovative method known as 'radio interferometry' to study the finer details of a radio source. To obtain higher spatial resolution for a given wavelength, radio astronomers apply the technique of interferometry. This involves collecting radio waves using two or more moderate-sized dish antennas, separated by several metres or kilometres and linked together by cables, to simultaneously study the same radio-emitting object. By electronically combining the signals received by each of the separate antennas it is possible to obtain a resolution that would otherwise need a dish antenna several kilometres in diameter. Thus a radio interferometer is basically an array of antennas that operate together as if they were a single instrument of very large aperture.

There are several celestial objects that emit more strongly in radio wavelengths than in visible wavelengths. No wonder, radio astronomy has produced many surprises in the past six decades. Most of the familiar objects in the visible sky – the stars and the planets – have turned out to be invisible in the radio sky because they do not emit any radio waves. On the other hand, some regions of the sky, where only faint stars are seen in visible light, have shown up as strong emitters of radio waves. One of the first discoveries made by using a radio telescope was the emission of radio waves from the Sun. By 1950, several other cosmic sources of radio waves were identified. They included the famous Crab nebula, and two galaxies – M87 and NGC 5218. Later, radio telescopes enabled planetary scientists to discover intense radio emissions from Jupiter and to measure the temperature of all the planets. By the mid-1980s some 100,000 cosmic radio sources had been catalogued.

By studying the sky with radio and optical telescopes, astronomers could gain much more complete understanding of the processes at work in the cosmos than possible with only optical telescopes. In addition, radar studies have shown that Venus, the surface of which always remains hidden behind thick clouds, rotates in the retrograde, or reverse, direction from that of the other planets. Radar measurements also have revealed the rotation of Mercury, which was previously thought to keep the same side toward the Sun. Utilising radio telescopes equipped with sensitive microwave spectrometers, researchers have discovered more than 50 separate molecules, including familiar chemical compounds like water vapour, formaldehyde, ammonia, methanol, ethanol, and carbon dioxide in space.

Powerful 'star-like' sources

But the really big discovery in radio astronomy came in 1960, when an entirely new class of astronomical objects never known before were detected in deep space. One of the first radio 'stars' discovered in 1960 that could be identified with a star in a photographic image was called 3C 48. It turned out to be an entirely new class of astronomical objects known as 'quasi-stellar radio sources' or quasars. These were point-like objects which appeared like stars in visible light but which also emitted extremely strong radio waves. A typical quasar was found to be no more than a light-year or two in size, but up to 1,000 times more luminous than giant galaxies that have a diameter of about 100,000 light-years. Measurement of the red shift of the light from these objects showed them to be extremely distant, a typical distance being more than 10,000 million light-years.

The question that puzzled astronomers was: what kind of energy source could produce the kind of brilliance that could be visible from such a large distance? To produce that kind of brilliance, quasars had to have an extremely powerful energy source and astronomers were convinced no star could produce such stupendous amounts of energy by conventional thermonuclear reactions. By the end of the 1960s, radio astronomers had discovered more than 150 quasars, although not all of them were found to emit strongly in radio wavelengths.

The prodigious source of energy of quasars still remains an enigma, although some astronomers attribute it to black holes embedded in galaxies. (Black holes are remnants of very massive stars and are so massive and so compact with so strong gravitational field that not even light can escape their staggering gravity.)

Little Green Men

By the end of the 1960s, with the discovery of quasars and several other radio sources in the sky, the tremendous potential of radio astronomy as an observation tool was proved beyond doubt and several refinements were already being tried out. Astronomers had designed instruments that could detect very short bursts of radio emission, making it possible to study fast changes in cosmic radio objects. One astronomer who was trying out such an arrangement was the English astronomer Anthony Hewish, who was directing a research project at the Cambridge University Observatory in UK.

In the mid-1960s the technique of interplanetary scintillation was discovered. Interplanetary scintillation is the apparent ‘twinkling’ of radio emissions from a compact radio source. The visible light from a distant star appears to twinkle when viewed from Earth, because the light has to pass through the Earth's turbulent atmosphere to reach us. The 'twinkling' of radio sources is not due to the Earth's atmosphere, but due to moving clouds of charged particles given off by the Sun. As radio waves pass through these moving 'solar winds' they are diffracted, making the radio source appear to twinkle when seen from Earth.

In the hope of finding quasars using interstellar scintillation Hewish designed a large radio telescope to detect the interplanetary scintillation. He believed radiation from a compact source would 'twinkle' more than radiation from an extended region, and so quasars should scintillate more than the other radio source. By looking for the twinkling radio sources, Hewish hoped to pick out lots of quasars.

Hewish's telescope took two years to build and covered an area of about two hectares. The telescope consisted of more than a thousand posts strung with more than 2,000 dipoles, and more than 190 kilometres of wire and cable was needed to carry the signals.

In August 1967, one of Hewish's students named Jocelyn Bell detected a strange signal coming from a direction midway between the bright stars Vega and Altair that fluctuated with uncanny regularity. The bursts were astonishingly brief, lasting only 1/30th of a second. No natural cosmic object could perhaps emit signals with such regularity. By January 1968, Hewish and Bell had found four of these pulsing sources. They wrote a paper describing the first source and submitted it to the journal *Nature*, where it was published on 24 February, 1968.

The discovery of the pulsating signals immediately put the astronomical fraternity in frenzy. Could the signals be

Jocelyn Bell's antenna that was instrumental in the discovery of pulsars.

artificial, sent out by some intelligent race elsewhere in the Galaxy? Such a possibility could not be ruled out altogether in the absence of an alternative explanation. Astronomers half-jokingly called them LGM for 'Little Green Men.'

To find out the truth, Hewish and his team kept monitoring the signals. A few days of observation convinced the scientists that the pulses were keeping time to better than one part in a million, which implied that whatever the nature of the object, it was acting like a high-precision clock. After a month's observation it became clear that the signals could not be originating from a planet, because if it were so the

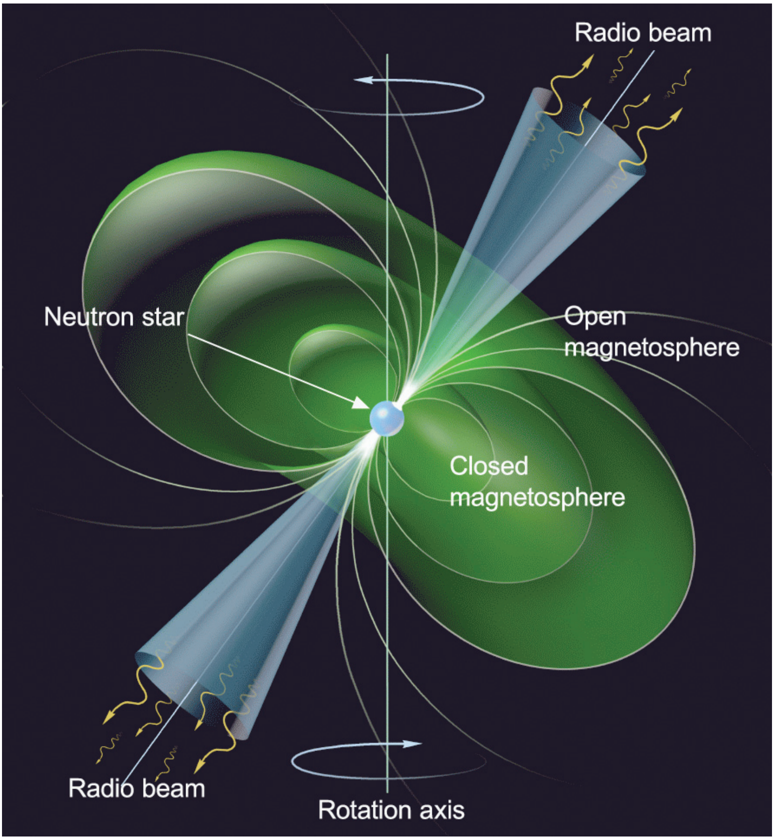


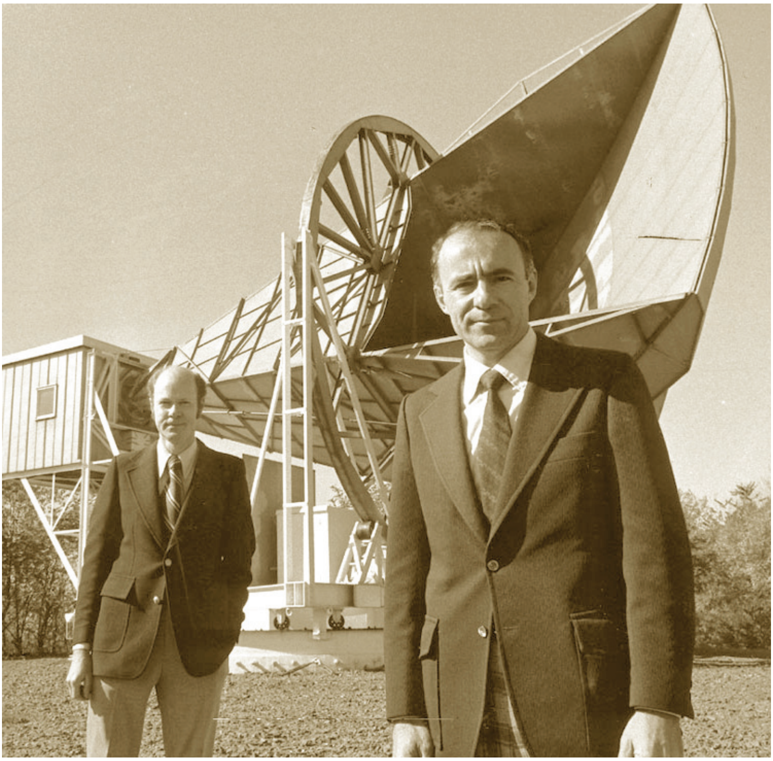
Diagram of a pulsar showing the rapidly spinning neutron star at the centre emitting strong radio beams.

planet's orbital motion would have led to a systematic variation in the periodicity of the pulses, which was not the case here. Soon, many more such objects were discovered, putting at rest any possibility of their link with any alien intelligent civilisations. They were natural cosmic objects the kinds of which were unknown before.

It did not take astrophysicists long to unravel the mystery. The British astrophysicist Fred Hoyle suggested that pulsars could be products of supernova explosions that mark the end of large stars. It was suggested that the pulses were coming from fast-spinning remnants of massive stars made up entirely of neutrons. Neutron stars, as these objects are called, are produced when massive stars explode as supernova at the end of their life. These tiny cosmic objects are only a few kilometres in diameter but are extremely dense; they contain as much matter as our entire Sun. As they spin rapidly they behave like cosmic 'lighthouses', sending out a radio beam that appears to flash rapidly when seen from Earth, just like a beam from a lighthouse or airport beacon appears to fluctuate to a distant observer. Thus, a fast rotating object could explain the rapid fluctuation of the radio signals. Astrophysicists had long speculated about the existence of neutron stars, but their discovery had to await the advent of radio astronomy. Because of the fluctuating radio signals sent out by fast-spinning neutron stars, they came to be known as pulsating stars, or 'pulsars' in short.

Relics from the past

Quasars and pulsars were not the only objects discovered after the advent of radio astronomy, it also provided a much-awaited proof of the Big Bang – the colossal event that is supposed to have brought this Universe into existence in a primeval fireball, some 10,000 to 20,000 million years ago. In that titanic cosmic event, the Universe began with rapid expansion of space, which has never ceased. As early as 1948, the famous American physicist George Gamow, in a paper he wrote with Ralph Alpher, made the remarkable prediction that, if indeed there were a Big Bang, the radiation accompanying this very hot early stage must have cooled down with the expansion of the Universe and should still be around today in the form of microwave radiation. It was



Arno Penzias and Robert Wilson standing before the horn antenna that detected cosmic microwave background radiation.

predicted that the microwave background radiation should be characteristic of objects at a temperature of about 5K (that is, 5 degrees above absolute zero) and should be coming from all parts of the sky as a homogenous background.

The elusive all-pervading background radiation was eventually detected in May 1964 by two scientists Arno Penzias and Robert Wilson, working at the Bell Telephone Laboratories, Holmdel, New Jersey, USA. Penzias and Wilson were experimenting with an ultra-sensitive, 6-metre horn antenna originally built to detect radio waves bounced off *Echo* balloon satellites. To measure these faint radio waves, they had to eliminate all recognisable interference from their receiver. They removed the effects of radar and radio broadcasting, and suppressed interference from the heat in the receiver itself by cooling it with liquid helium to –269°C. But still, a low, steady, mysterious noise persisted in their receiver. This residual noise was 100 times more intense than Penzias and Wilson had expected; it was evenly spread over the sky, and was present day and night. They were certain that the 7.35-centimetre radiation they detected did not come from the Earth, the Sun, or our galaxy. Both concluded that this noise was coming from outside our own galaxy – although they were not aware of any radio source that would account for it.

To find out what could be the source of the noise, Penzias and Wilson consulted Princeton physicist Robert H. Dicke, who had theorised that if the Universe was created according to the Big Bang theory a background radiation at 3° Kelvin would exist throughout the Universe. Dicke visited Bell Labs and confirmed that the mysterious radio signal Penzias and Wilson detected was, indeed, the cosmic radiation that had survived from the very early days of the Universe. It was proof of the Big Bang.

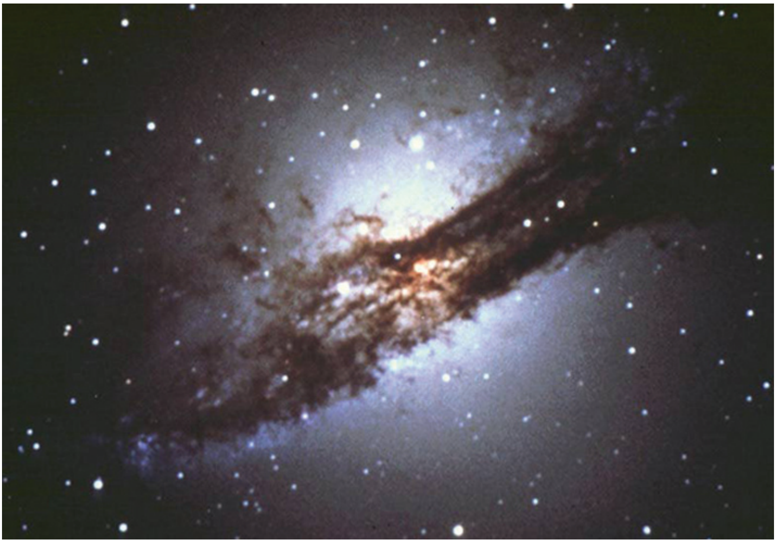
Large arrays of antennas

As any astronomer would know, the resolving power of an optical telescope depends on the size of the objective lens or mirror. (The resolving power denotes the ability of a telescope to separate two close objects, when viewed from a distance.) Larger the size of the objective the higher would be the resolving power. Resolving power is also a function of the wavelength of light; longer the wavelength larger would the required diameter of the objective be for better resolution. When dealing with radio waves, however, things

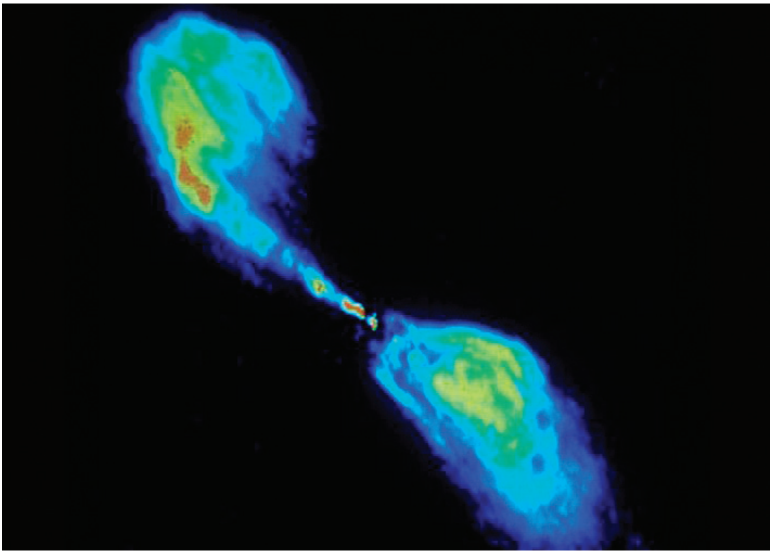
The Very Large Array (VLA) radio telescope in New Mexico, USA, consists of 27 parabolic dishes that are each 25 metres in diameter and uses the technique of radio interferometry.

become a bit tricky. As we all know, radio waves are more than 10,000 million times longer than light waves. So, to have the same resolving power, a radio telescope ought to have a dish antenna 10,000 million times bigger! Of course, that is quite an absurd suggestion. But the size of the dish antenna indeed turned out to be a major constraint in radio astronomy, till radio astronomers came out with a bright idea. Rather than building a single giant antenna, they decided to use a large array of smaller dishes that together could act as a single antenna of enormous size. The largest array in operation today is the Very Large Array (VLA) radio telescope set up in New Mexico in the US, which uses the technique of radio interferometry, as described earlier.

The VLA, which went into operation in 1980, consists of 27 parabolic dishes that are each 25 metres in diameter. Each



Centaurus A photographed in optical wavelengths.



Centaurus A images by VLA in radio wavelengths. A pair of narrow "jets" appears to be shooting out of the galaxy, with the radio emission becoming more diffuse at greater distances from the galaxy centre. What makes these jets so unusual is their orientation. They are perpendicular to the dust disk.

of these dishes is mounted on a transporter that can be moved along rails laid out in an enormous Y pattern. Each arm of this pattern is about 21 kilometres long. The radio signals recorded by the component dishes are integrated by computer so that the entire array acts as a single radio antenna with a maximum effective aperture of 27 kilometres; that is, the array behaves like a single dish antenna 27 kilometres in diameter, which would be impossible to build. This large aperture gives the VLA a resolving power equal to that of the best ground-based optical telescopes.

The world's largest radio telescope array at metre wavelength is located near Pune in India. Known as the Giant Metre-wave Radio Telescope (GMRT) it is an array of 30 fully steerable parabolic dish antennas, each 45 metres in diameter. Twelve of these are located in a compact central

The Giant Metre-wave Radio Telescope (GMRT) it is an array of 30 fully steerable parabolic dish antennas, each 45 metres in diameter.

array, about 1 km × 1 km in size. The remaining 18 antennas are placed along the three arms of an approximately Y-shaped configuration with each arm extending to about 14 kilometres from the array centre. GMRT is the world's most powerful radio telescope operating in the frequency range of about 50 to 1500 MHz. The large size of the parabolic dishes implies that GMRT will have over three times the collecting area of the VLA. The GMRT will be about eight times more sensitive than VLA because of the larger collecting area, higher efficiency of the antennas and a substantially wider usable bandwidth. Already some startling observations of supernova remnants and radio galaxies have been made using the GMRT.

The world's newest radio telescope, the Atacama Large Millimetre Array (ALMA), is coming up in the Atacama Desert of northern Chile at an altitude of 5,000 metres. It is a millimetre-wave interferometer consisting of at least 66 antennas and when completed in 2012 will be the leading astronomical instrument for observing the cool Universe – the molecular gas and dust that constitute the building blocks of stars, planetary systems, galaxies, and of life itself. ALMA is a partnership between the scientific communities of East Asia, Europe and North America with Chile.

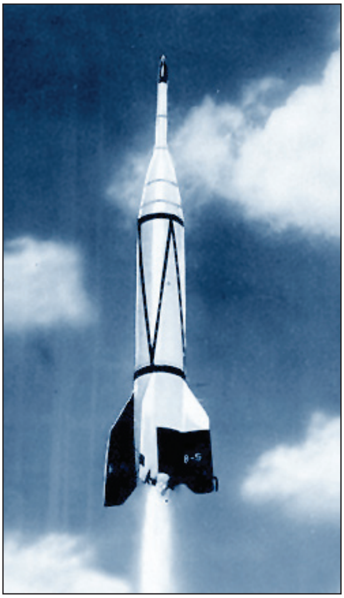
Indeed radio telescopes like the VLA, GMRT, and ALMA are revolutionising our ideas about the Universe, showing it to be filled with violent activity the like of which had been never known before. By being able to look back in time they are also throwing new light on the origins of the Universe and its evolution over thousands of millions of years to its present state.

6

Observing from space

As we have seen, the Earth's atmosphere is opaque to a large part of the electromagnetic spectrum. As a result, radiation in infrared, extreme ultraviolet, X-ray, and gamma-ray wavelengths cannot reach ground-based telescopes or detectors and it is almost impossible to observe the sky in these wavelengths from the ground. The dawn of the Space Age in the 1950s came as a boon for astronomers, for it opened up enormous possibilities of observing the cosmos in wavelengths that are inaccessible from the ground.

Before the first satellite was put into orbit in 1957, rockets were used for various astronomical studies from above the Earth's atmosphere. Rocket research gave rise to three new branches of astronomy – ultraviolet, X-ray, and gamma ray. X-ray astronomy began after the Second World War when a large number of captured German V2 rockets were made available to scientists in USA for small experiments in sub-orbital flight. X-rays from Sun were first detected in 1949 by sending detectors beyond Earth's atmosphere on board a V2 rocket.

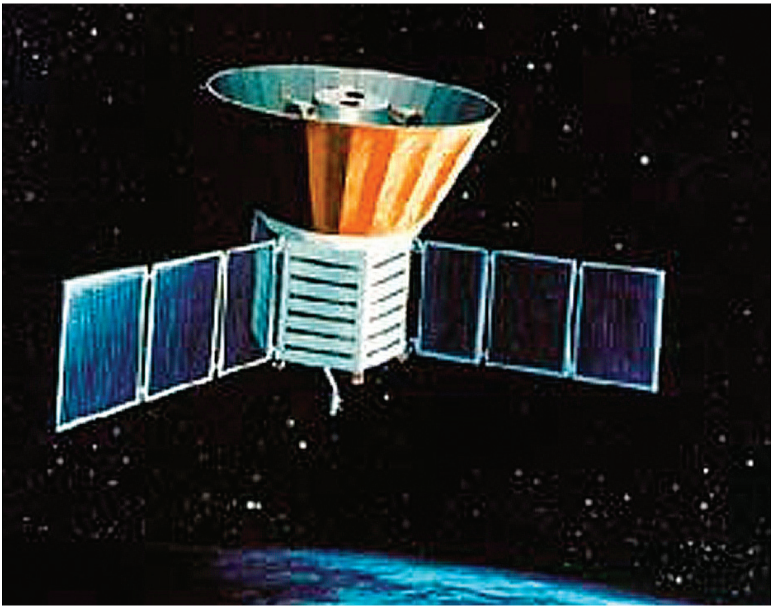


American V2 rocket carrying X-ray detectors

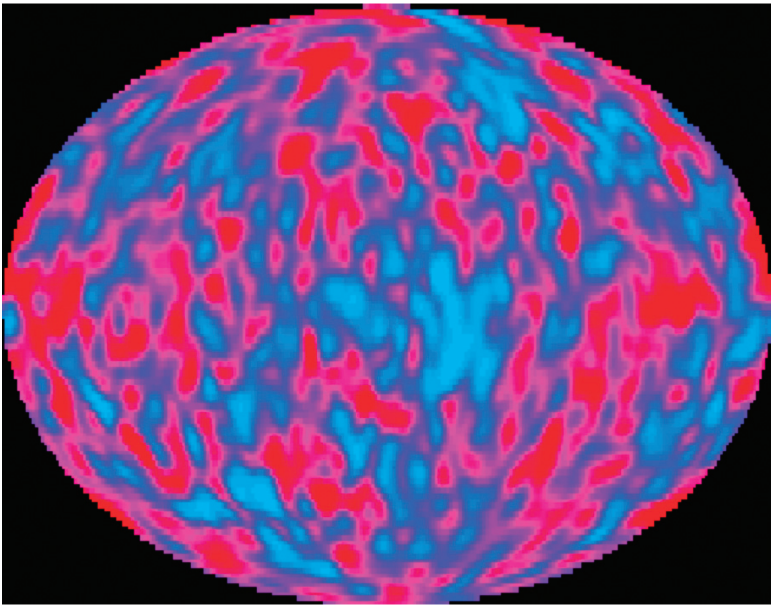
Because the science payload does not go into orbit, rocket missions do not need expensive boosters or extended telemetry and tracking coverage. As a result, mission costs are substantially less than those required for orbiter missions. In the latter half of the twentieth century, advances in instrumentation and improved observational techniques, especially space-borne detectors, have led to the discovery of numerous cosmic sources that emit in infrared, X-ray and gamma ray wavelengths

The *Cosmic Background Explorer*

The discovery of the cosmic microwave background radiation in 1964 by Arno Penzias and Robert Wilson proved beyond doubt that Big Bang was a reality. But it did not



The Cosmic Background Explorer *(COBE) was a satellite designed to investigate the cosmic microwave background radiation.*



Map of the sky photographed by COBE *showing 'cosmic ripples' – tiny fluctuations in the temperature of the cosmic microwave background.*

provide a complete picture of the early Universe in terms of the detected radiation. The *Cosmic Background Explorer* (*COBE*) was a satellite designed to do that. Its goals were to investigate the cosmic microwave background radiation and provide measurements that would help shape our understanding of the cosmos. The satellite was launched in November 1989 by NASA. Over the next four years, *COBE* mapped the brightness of the entire sky at several infrared wavelengths and discovered that the cosmic background radiation is not entirely smooth, showing extremely small variations in temperature in patches. Its historic discovery of 'cosmic ripples' – tiny fluctuations in the temperature of the cosmic microwave background – was announced in 1992. Cosmologists believe these variations may have led to the formation of galaxies. *COBE* also mapped interstellar and interplanetary dust clouds. *COBE* data showed that 99.97

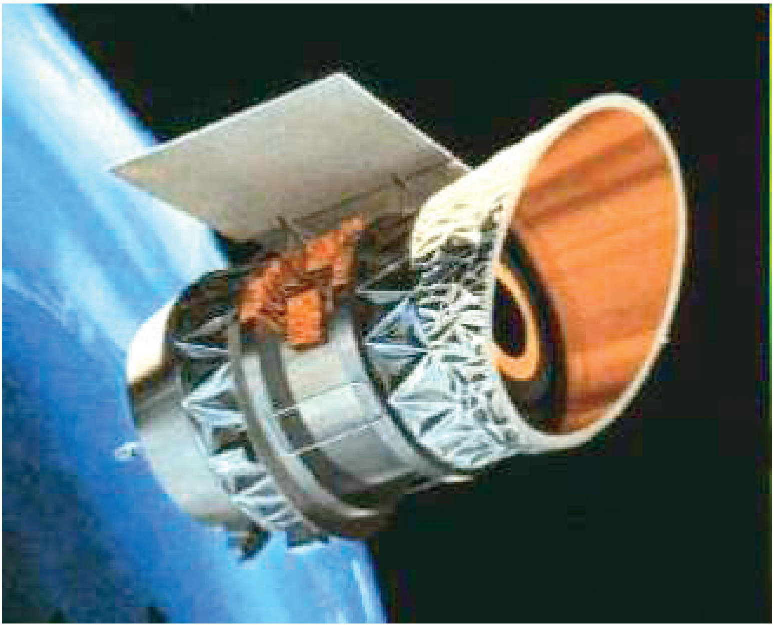
percent of the energy of the Universe was released in the first year after the Big Bang, suggesting that only one colossal explosion created the Universe.

ESA's Planck *space observatory is designed to observe the directional variations (anisotropies) of the cosmic microwave background radiation field over the whole sky, with unprecedented sensitivity and angular resolution.*

Another satellite to study the cosmic background radiation was launch in May 2009. ESA's *Planck* space observatory is designed to observe the directional variations (anisotropies) of the cosmic microwave background radiation field over the whole sky, with unprecedented sensitivity and angular resolution. Named in honour of the German physicist Max Planck, the satellite will provide a major source of information relevant to several cosmological and astrophysical issues, such as testing theories of the early universe and the origin of cosmic structure and is expected to provide answers to many fundamental questions about the early history and evolution of our universe.

Infrared satellites

Till the advent of satellites, astronomers had used numerous techniques go beyond the Earth's atmosphere in order to have a better view of the sky in infrared wavelengths. High-flying aircraft, balloons, and rockets were all used, but with only limited success. The first satellite exclusively devoted to infrared imaging of the sky was launched by NASA in

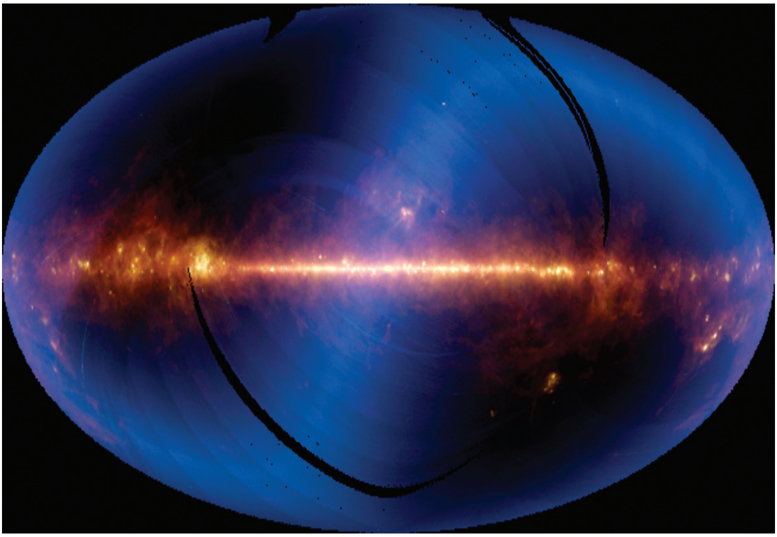


The Infrared Astronomical Satellite (IRAS) *was the first satellite exclusively devoted to infrared imaging of the sky. It carried a 57-cm telescope cooled to a temperature of 2.5o above absolute zero to infrared sources in the sky.*

January 1983. Called *Infrared Astronomical Satellite* (*IRAS*), it carried a 57-cm telescope cooled to a temperature of 2.5° above absolute zero and was operated jointly by the United States, United Kingdom and the Netherlands.

An infrared telescope, like the one used in *IRAS*, is almost identical to an optical telescope because infrared radiation behaves almost like visible light and can be reflected by mirror or focussed by a convex lens. In fact, as any photographer knows, all modern photographic cameras can be used for infrared photography using a special filter. This is exactly what was done in *IRAS*. The optics is the same as in any optical telescope; with a primary parabolic concave mirror and a secondary convex mirror for focussing the incident radiation. The only difference is that the whole system is cooled to a temperature of liquid helium (minus 268.9°C) to minimise the emission of infrared radiation from the telescope itself. After focussing the received infrared radiation it is passed through filters that allow infrared radiation of only a few specific wavelengths to fall on the detectors placed at the focal plane. (*IRAS* operated at wavelengths of 12, 25, 60, and 100 microns.) For detecting infrared radiation, solid-state semiconductor photo-detectors, arranged in arrays, was used in *IRAS*.

IRAS was the first observatory to perform an all-sky survey at infrared wavelengths. It was launched in January of 1983 into a sun-synchronous near-polar (99 degree) orbit, and functioned till November 1983. During its 10-month mission it mapped 96% of the sky four times. *IRAS* detected about 350,000 infrared sources, which included a disk of dust grains around the star Vega, six new comets, and very strong



IRAS *image of the Milky Way. The bright horizontal band is the plane of the Milky Way, with the centre of the Galaxy located at the centre of the picture.*

infrared emission from interacting galaxies as well as wisps of warm dust called infrared cirrus which could be found in almost every direction of space. *IRAS* also revealed for the first time the core of our galaxy, the Milky Way.

Computer-processed visible images created from *IRAS* data revealed the sky to have a striking appearance at infrared wavelengths. For example, whole-sky images showed two bright intersecting bands, one associated with the plane of Earth's orbit around the Sun (ecliptic plane), and the other with the plane of the Milky Way. The glow from the ecliptic plane has been ascribed to the heating of interplanetary dust in the solar system by the Sun. The glow in the plane of the Milky Way is due to heated interstellar dust, but much cooler than that in the solar system. An interesting feature of the infrared view of the Milky Way is that while in visible light the centre of the Milky Way galaxy (which lies in the direction of the constellation of Sagittarius) appears dark because it lies hidden behind a thick cloud of interstellar dust, in infrared it appears as the brightest region in the sky! This is because, with longer wavelengths, infrared radiation can penetrate the thick dust clouds that obscure the centre of the Milky Way galaxy in visible light.

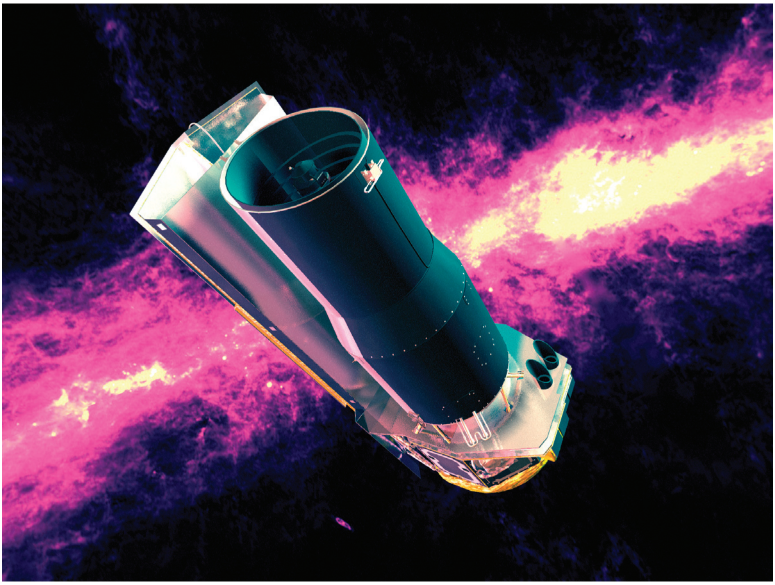
The *IRAS* data have already helped astronomers uncover a few surprises lying hidden in cool cosmic matter ranging in distance from a few million kilometres to several million light-years away. Among them are galaxies that are almost 100 times more luminous at infrared wavelengths than in visible wavelengths. In the area around the famous Great Nebula in the constellation of Orion, which has been known to be an active star-forming region, *IRAS* found an extensive complex of cold dust and gas highlighted by areas brightened due to heating by massive young stars embedded in the cloud or nearby. Only a small part of the *IRAS* data has been analysed so far. It may take several years to process the entire data gathered by *IRAS*. May be, we have still more surprises in store in the infrared sky!

Infrared Space Observatory

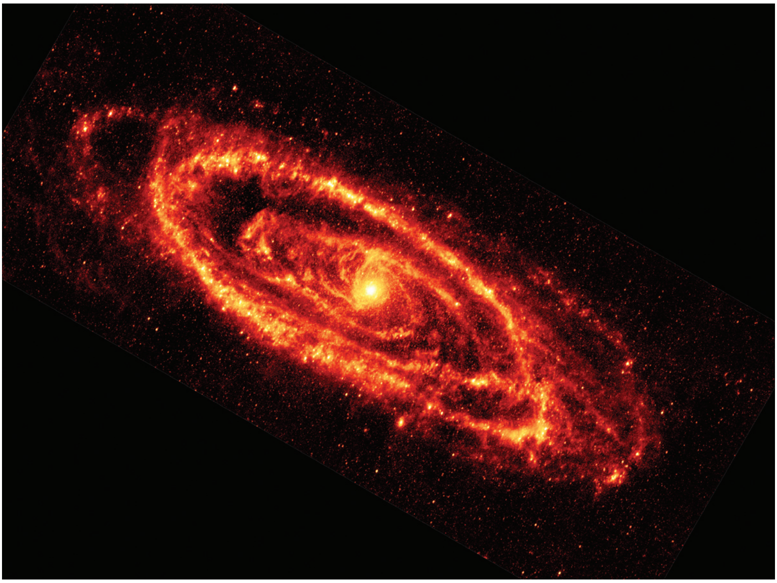
IRAS's successor was the European Space Agency's *Infrared Space Observatory* (*ISO*), which operated from November 1995 to May 1998. *ISO* observed in the range from 2.5 to 240 microns with greater sensitivity and resolution than its predecessor, and made the startling discovery that water vapour is a common and important part of the interstellar medium. The satellite found water in the vicinity of stars both at the beginning and end of their lives, in sources close to the centre of the galaxy, and in the atmospheres of planets in our Solar System. *ISO* also discovered that most ultra-luminous galaxies appear to be powered by starbursts rather than by black holes.

Spitzer Space Telescope

The Spitzer Space Telescope (formerly *SIRTF*, the *Space Infrared Telescope Facility*) was launched into space by NASA in August 2003. During its mission, *Spitzer* will obtain images and spectra by detecting the infrared energy, or heat, radiated by objects in space between wavelengths of 3 and 180 microns. *Spitzer* is a part of NASA's Astronomical Search for Origins Program, designed to provide information which will help us understand our cosmic roots, and how galaxies, stars and planets develop and form. Consisting of a 85-centimetre telescope and three cryogenically-cooled science instruments, *Spitzer* is the largest infrared telescope ever launched into space. Its highly sensitive instruments give us a unique view of the Universe and allow us to peer into regions of space which are hidden from optical telescopes.



Spitzer Space Telescope *is the largest infrared telescope ever launched into space.*

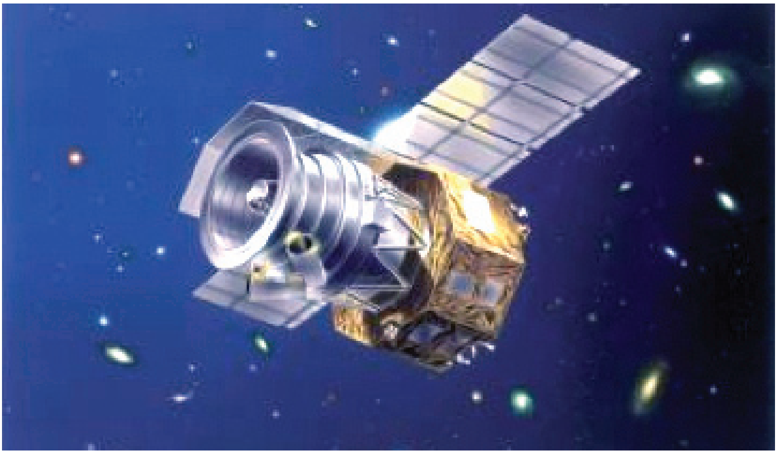


Spitzer *image of Andromeda galaxy in infrared.*

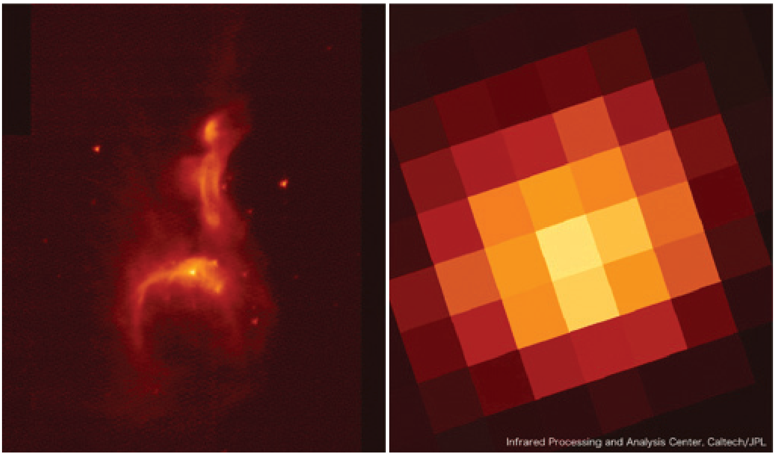
With the stock of liquid helium needed to chill some of its instruments to operating temperatures having run out, the primary mission of *Spitzer* came to an end in May 2009 after more than five-and-a-half years of probing the cosmos with its keen infrared eye. The telescope then started its 'warm' mission with two channels of one instrument still working at full capacity. The telescope's two shortest-wavelength detectors in its infrared array camera continue to function perfectly. They will still pick up the glow from a range of objects: asteroids in our solar system, dusty stars, planet-forming disks, gas-giant planets and distant galaxies. In addition, *Spitzer* still will continue to be able to see through the dust that permeates our galaxy and blocks visible-light views.

AKARI

In February 2006, yet another satellite dedicated to infrared astronomy was launched by Japan. Named *AKARI* (meaning 'light' in Japanese), the satellite carries the world's first



AKARI *infrared astronomy satellite, launched by Japan in 2006, carries the world's first infrared telescope mirror made out of silicon carbide.*

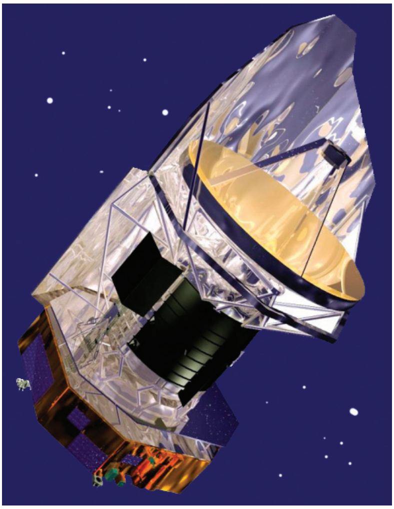


AKARI *(left) and* IRAS *(right) images of Reflection Nebula IC4954 showing the much higher resolution of the former.*

infrared telescope mirror made out of silicon carbide (68.5-cm diameter). As well as being light and robust, silicon carbide undergoes virtually no thermal expansion with temperature, enabling much higher resolution than possible with glass mirrors. The purpose of the *AKARI* mission is to survey the entire sky in infrared light with much higher resolution than was possible with *IRAS*. In addition, *AKARI* will also perform detailed observations of selected astronomical objects.

Herschel Space Observatory

The *Herschel Space Observatory*, launched in May 2009 by NASA, is a space-based telescope that will study the Universe by the light of the far-infrared and sub-millimetre portions of the spectrum (wavelength 60-670 microns). Named after the German-born English astronomer William Herschel, the space observatory is expected to reveal new information about the earliest, most distant stars and galaxies, as well as those closer to home in space and time. It will also take a unique look at our



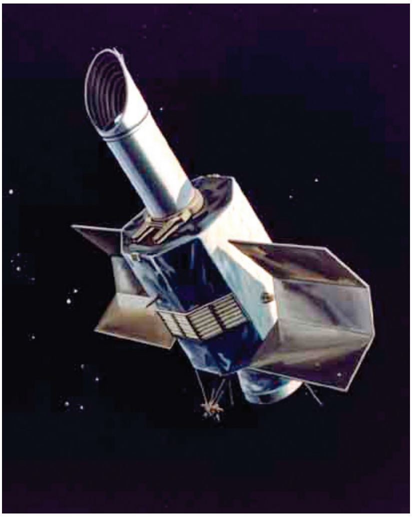
The Herschel Space Observatory, *launched in May 2009, is a space-based telescope that will study the Universe by the light of the far-infrared and sub-millimetre portions of the spectrum.*

own solar system. Ten countries, including the United States, participated in its design and implementation. With a primary mirror 3.5 metres in diameter, *Herschel* will be the largest infrared telescope sent into space as of its launch date and will be the first spacecraft to observe in the full 60-670 microns range.

The far-infrared and sub-millimetre wavelengths at which *Herschel* will observe are considerably longer than the visible wavelengths that the human eye can perceive. Yet, this is a critically important portion of the spectrum to scientists because it is the frequency range at which a large part of the Universe radiates. Earthbound telescopes are largely unable to observe this portion of the spectrum because most of this light is absorbed by moisture in the atmosphere before it can reach the ground. Previous space-based infrared telescopes have had neither the sensitivity of *Herschel*'s large mirror, nor the ability of *Herschel*'s three detectors to do such a comprehensive job of sensing this important part of the spectrum.

The cosmos in ultraviolet

The first successful attempt to photograph the Sun in ultraviolet was made in 1946, when a rocket-borne camera did the job. Since the early 1960s, the United States and several other countries have placed in Earth orbit unmanned satellite observatories for ultraviolet imaging of the sky. The first such instruments were the eight *Orbiting Solar Observatories* placed in orbit between 1962 and 1975. These satellites measured ultraviolet radiation from the Sun. The data collected from these telescopes provided scientists with a much more complete picture of the solar corona, the outermost part of the Sun's atmosphere.



The International Ultraviolet Explorer, *launched by NASA in 1978, is the most successful ultraviolet satellite to date.*

Another series of four space observatories called the *Orbiting Astronomical Observatory* (*OAO*) satellites were launched by NASA between 1966 and 1972, which provided the first high-quality observations of many objects in ultraviolet light. While two *OAO* missions were failures, the other two provided valuable information on a variety of subjects, including thousands of stars, a comet, a nova in the constellation of Serpens, and some galaxies beyond.

The most successful ultraviolet satellite to date was the *International Ultraviolet Explorer* (*IUE*) launched by NASA in January 1978. The *IUE* was a joint project of the United States, Great Britain, and the European Space Agency. With very sensitive equipment, the *IUE* studied planets, stars, galaxies, nebulae, quasars, and comets. It recorded especially valuable information from novae and supernovae. The satellite sent back data that supported the theory that a black hole with the mass of a thousand solar systems exists at the centre of our Milky Way galaxy. The data also provided evidence of gravitational lensing by a massive galaxy as being responsible for the so-called 'twin quasars' image. Here the strong gravitation field of the massive galaxy bends the light coming from the distant quasar, as predicted by Einstein's relativity theory, to produce the double image. The *IUE* also discovered that our Milky Way galaxy is surrounded by a halo of hot gases. Although intended to function for only three to five years, the *IUE* operated until September 1996, making it the longest-lived astronomical satellite.

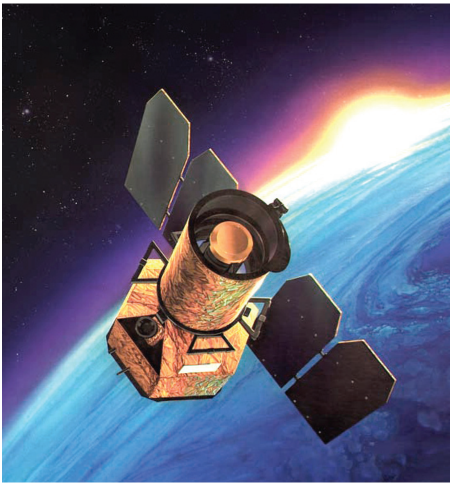
The extreme ultraviolet region of the electromagnetic spectrum (wavelength 7-76 nanometres) is a particularly difficult region to observe. Light at these wavelengths is absorbed rather than reflected by conventional telescope mirrors. It also is absorbed by all but the thinnest materials. Therefore, components used in standard telescopes and spectrometers, such as lenses, filters, and transmission gratings, cannot be used for extreme ultraviolet studies. Similarly, ordinary visible light and ultraviolet light detectors cannot be used at these wavelengths because their protective covers absorb the extreme ultraviolet light, preventing it from reaching the actual detection devices. As a result astronomical studies in the extreme ultraviolet region had been minimal.

In order to fill this gap the *Extreme Ultraviolet Explorer* (*EUVE*) was launched by NASA in June 1992. It was equipped with three grazing incidence scanning telescopes and an extreme ultraviolet spectrometer/deep survey instrument to carry out mapping of the entire sky in extreme ultraviolet region. The satellite observed approximately 350 astronomical targets before re-entering the atmosphere in January 2002.

Another satellite-borne ultraviolet telescope, the *Far Ultraviolet Spectroscopic Explorer* (*FUSE*), was launched in June 1999 by NASA. *FUSE* was designed to look farther into the ultraviolet (wavelength 90.5-119.5 nanometres) than the *IUE*. With *FUSE*, astronomers hoped to study high-energy processes in stars and galaxies in addition to exploring conditions in the Universe as they existed only shortly after the Big Bang. The satellite functioned till June 2007.

GALEX

In April 2003, NASA launched the *Galaxy Evolution Explorer* (*GALEX*) with a unique goal – to make observations at ultraviolet wavelengths to measure the history of star formation in the universe in the distant past. The satellite carries a telescope with a 50-centimetre-diameter mirror and state-of-the-art ultraviolet detectors that will study the shape, brightness, size and distance of galaxies across 10 billion years of cosmic history to help astronomers determine when the stars we see today had their origins. A galaxy's ultraviolet brightness tells us how fast its stars are forming.



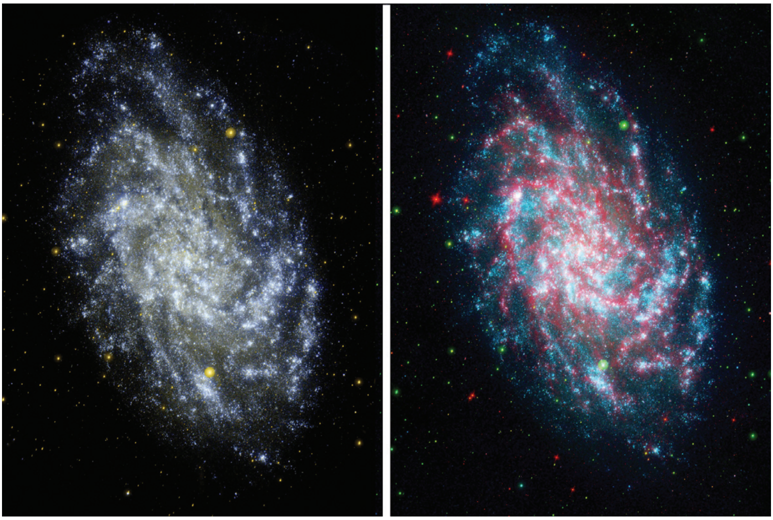
The Galaxy Evolution Explorer (GALEX) *was launched by NASA in 2003 with a unique goal – to make observations at ultraviolet wavelengths to measure the history of star formation in the universe in the distant past.*

GALEX mission scientists have been looking for stars whose appearance reveals them to be young.

These are the most massive stars, which are so hot they shine in ultraviolet wavelengths. So, looking in ultraviolet wavelengths helps single out galaxies dominated by young, hot, short-lived stars that give off a great deal of energy at that wavelength. These galaxies are actively creating stars, therefore providing a window into the history and causes of galactic star formation.

Since its launch in April 2003, *GALEX* has imaged more than 50 million objects across two-thirds of the sky and have detected star formation in unexpected regions of the universe.

Scientists would like to understand when the stars that we see today were formed, and when the chemical elements that make up our Milky Way galaxy formed. Chemical elements are known to have been formed in the interiors of

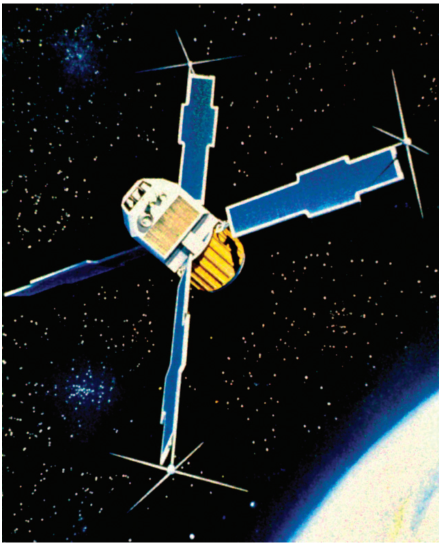


In these two images of M33, the ultraviolet image on the left was taken by the GALEX, *while the ultraviolet and infrared image on the right is a blend of the mission's M33 image and another taken by NASA's* Spitzer Space Telescope.

stars, but we don't know when. Information gathered by the *GALEX* mission will fill in one of the missing pieces of the puzzle to explain how the visible universe came to be.

X-ray observatories

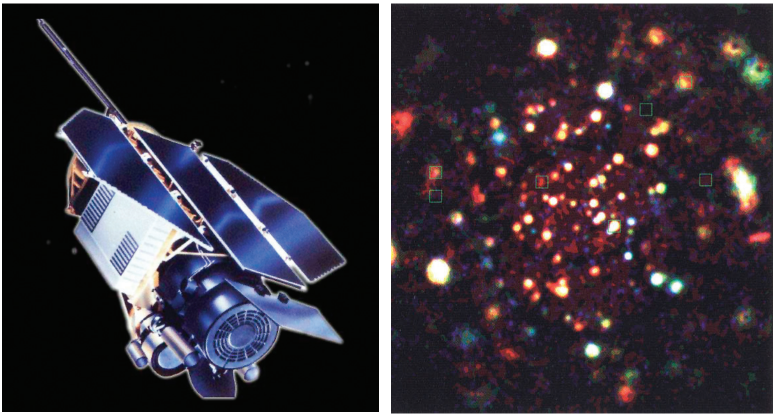
The discovery of the first X-ray source outside the solar system came in 1962, when an American *Ranger* spacecraft was on a mission to the Moon. It happened by chance to discover a very strong X-ray source in deep space. As it was discovered in the direction of the constellation of Scorpius, the source came to be known as Sco X-1. The object was later found to be associated with a faint star and was emitting 1,000 times more energy as X-rays than at visible wavelengths. The discovery pointed to the fact that, besides our Sun there were certainly distant and more powerful X-ray sources as well.



Launched in 1970, Uhuru *was the first satellite devoted to X-ray astronomy.*

The first satellite devoted to X-ray astronomy was *Uhuru*, which was launched in December 1970. The satellite detected more than 300 sources of X-ray emission in the sky during its two-year life span. One major scientific result of *Uhuru* was the discovery that a large fraction of the cosmic X-ray sources detected are binary systems in which matter from a normal star is falling onto an extremely dense object, such as a white dwarf, a neutron star, or a black hole. These binary systems were found to emit almost 1,000 times more energy in X-ray wavelengths than the Sun radiates in all wavelengths. Later, as more refined techniques were developed and more advanced satellites were put into orbit, more celestial X-ray sources were discovered. Prominent among them are the Crab Nebula in the constellation of Taurus and Cyg X-1 in the constellation of Cygnus.

In June 1990, another X-ray observatory called the *ROentgen SATellite* (*ROSAT*) was launched by NASA. Named in honour of the German physicist Wilhelm Roentgen, the satellite was developed through a cooperative program between Germany, the United States, and the United Kingdom and carried a German-built imaging X-ray telescope. It was designed and operated by Germany. *ROSAT* performed the first all sky surveys with imaging telescopes leading to the discovery of a total of 150,000 X-ray sources, twenty-five times more than with all previous



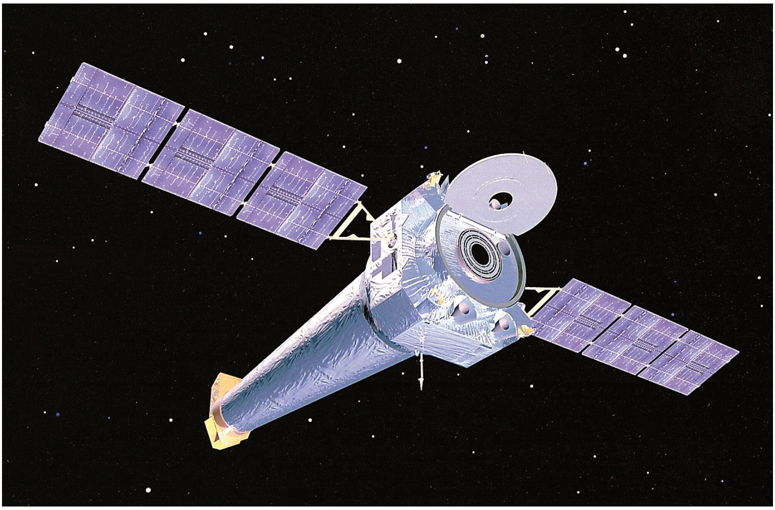
ROSAT *(left) and false colour image of the Pleiades cluster (right) was produced from* ROSAT *observations by translating different X-ray energy bands to visual colours - the lowest energies are shown in red, medium in green, and highest energies in blue.*

X-ray satellites together. In addition it mapped the diffuse galactic X-ray emission with unprecedented angular resolution of less than 1 arc minute. *ROSAT* was switched off in February 1999 after 8½ years of successful operation.

Chandra X-ray Observatory

One of the most powerful space-borne observatories – an X-ray telescope – to study X-rays from the stars and galaxies was launched by NASA in 1999. It is named *Chandra X-ray Observatory* in honour of the Indian-born Nobel laureate Subrahmanyan Chandrasekhar, who is known for his pioneering work on evolution of stars.

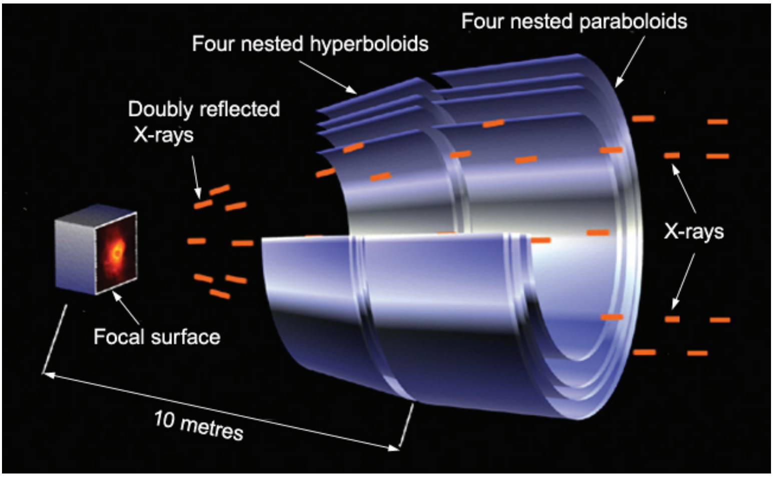
An X-ray telescope is a very special form of telescope. An ordinary telescope would be of no use because the X-rays do not reflect off mirrors the same way that visible light does. Because of their high energy, X-ray photons would



The Chandra X-ray Observatory, *launched by NASA in 1999, is a powerful space-borne observatory to study X-rays from the stars and galaxies.*

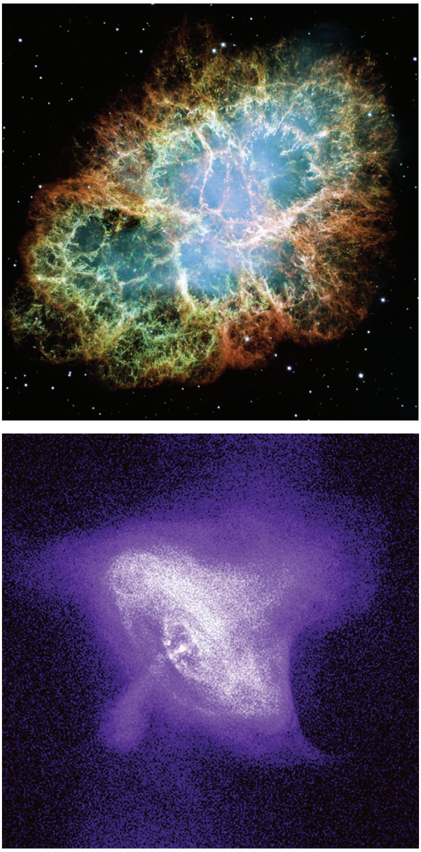
simply penetrate into the mirror in much the same way that bullets slam into a wall. In a similar way, just as bullets ricochet when they hit a wall at a grazing angle, so too do X-rays ricochet off highly polished mirrors. X-ray telescopes make use of this property of X-rays to focus them for getting images with high resolution.

Compared to the earlier X-ray telescopes, the *Chandra X-ray Observatory* is a really big telescope. The length of *Chandra* is 13.8 metres. But what made *Chandra* really an advanced instrument at the time were its mirrors that are used to focus X-rays. At the heart of the *Chandra* telescope system is the high-resolution mirror assembly. Since high-energy X-rays would penetrate a normal mirror, special cylindrical mirrors were created – shaped and polished with extreme precision. The two sets of four nested mirrors resemble tubes within tubes. They can bring X-rays from distant sources to a much sharper focus than ever possible. In other words, images received from *Chandra* are much



Chandra *mirror assembly. It uses two sets of four barrel-shaped nested mirrors to bring X-rays from distant sources to a sharp focus.*

more detailed than any obtained before it. Sharper images allow astronomers to see not only fainter objects but also finer details.



Crab Nebula in visible light (top) and in X-ray taken by Chandra observatory (bottom). The X-ray image shows the central pulsar surrounded by tilted rings of high-energy particles that appear to have been flung outward over a distance of more than a light year from the pulsar. Perpendicular to the rings, jet-like structures produced by high-energy particles blast away from the pulsar.

Another unique feature of *Chandra* is its orbit. Unlike all the previous satellites including the Hubble Space Telescope, which is placed in a circular orbit, *Chandra* has been placed in a highly elongated orbit, which brings it to within 10,000 km of the Earth at its nearest approach and takes it as far away as 140,000 km at its farthest point in orbit every 64.2 hours. At its farthest point *Chandra* is fully one third of the way to the Moon!

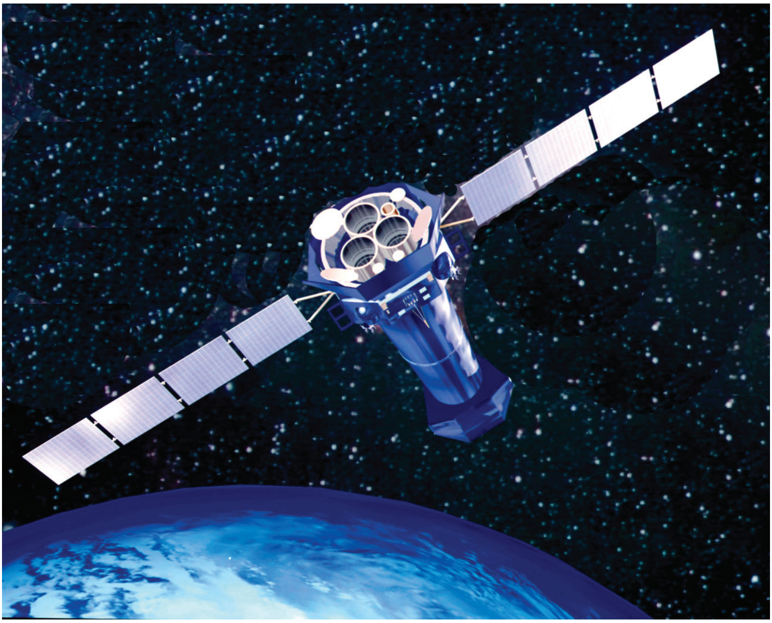
In the past ten years *Chandra* has made some remarkable discoveries. In April 2002, NASA announced the discovery of an entirely new kind of star unknown before. The announcement, based on results from *Chandra*, said the new star is possibly entirely made of fundamental particles called quarks. The unique thing about this star is that it is only a few kilometres across but weighs more than our Sun. The star, called RX J1856 is about 360 light years from Earth and if it were really made of quarks it would be the first example of its kind.

Theoreticians had hypothesised the existence of quark stars in the 1980s, but none could be detected earlier. The star RX J1856 was previously thought to be a neutron star – formed when a large star explodes and its core collapses (neutron stars are also known as pulsars). At this stage, gravitational attraction between particles in an atom overcomes the electrical repulsion keeping them apart, fusing protons and electrons to form neutrons, which pack together at unimaginable density. A teaspoonful of neutron star would weigh a thousand million tonnes!

But *Chandra*'s measurements suggested that, at just over 11 kilometres across, RX J1856 is too small to be a neutron star. Instead, neutrons and protons in the star may themselves have dissolved into an even denser mass of their constituent quarks, creating what astronomers call 'strange matter', in which the packaging of three constituent quarks in a proton or neutron breaks down resulting in the densest form of matter theoretically possible. Here again, it was space technology that led to the discovery of yet another strange cosmic object the existence of which would not have been imagined just two decades ago.

XMM-Newton

The European Space Agency's X-ray multi-mirror satellite *XMM-Newton*, launched in December 1999, is the most powerful X-ray telescope ever placed in orbit. Named in honour of the English physicist Isaac Newton, the satellite carries three very advanced X-ray telescopes. They each



ESA's X-ray multi-mirror satellite XMM-Newton, *launched in 1999, is the most powerful X-ray telescope ever placed in orbit.*

contain 58 high-precision concentric mirrors, delicately nested to offer the largest collecting area possible to catch the elusive X-rays. These mirror modules allow *XMM-Newton* to detect millions of sources, far more than any previous X-ray telescope. Scientists are hopeful the mission will help solve many cosmic mysteries, ranging from enigmatic black holes to the formation of galaxies.

The orbit of *XMM-Newton* is similar to that of *Chandra* – it is also highly eccentric, extending to nearly one third of the distance to the Moon at its farthest, which would enable very long and uninterrupted observations. Peering into deep space, *XMM-Newton*'s science payload will considerably increase our knowledge of very hot objects created when the Universe was very young.

Rossi X-ray Timing Explorer Mission

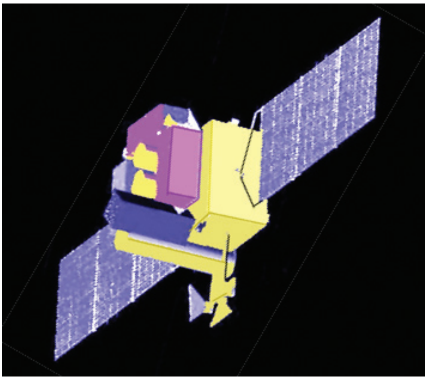
The *Rossi X-ray Timing Explorer* (*RXTE*) is a satellite designed to observe the fast-moving, high-energy worlds of black holes, neutron stars, X-ray pulsars and bursts of X-rays that light up the sky and then disappear forever. The satellite was launched into low-Earth orbit in December 1995.

Astronomers study changes that happen from microseconds to months in cosmic objects to learn about how gravity works near black holes; how pulsars in binary systems are affected by mass transferring from one star to the other; and how the distant galaxies are powered. Some pulsars spin faster than a thousand times a second. And a neutron star produces extremely powerful gravitational pull that attracts matter from the surrounding with extreme force. *RXTE* will allow observation of such events happening in the distant Universe with accurate timings and contribute to our understanding of these extreme objects. *RXTE* is designed to observe changes in X-ray brightness that occur in a mere thousandth of a second, or over several years.

More X-ray space missions are planned for the coming decades. Among them is the *International X-ray Observatory* (*IXO*), which is a new X-ray telescope with joint participation from NASA, the European Space Agency (ESA), and Japan's Aerospace Exploration Agency (JAXA). Likely to be launched in 2020, *IXO* would be an X-ray observatory dedicated to high resolution X-ray spectroscopy, with 100 times the throughput for high resolution spectroscopy of previous X-ray observatories. The spacecraft will feature a single large X-ray mirror and an extendible optical bench, with a focal length of 20 metres, and a suite of six focal plane instruments. The instruments under study for the *IXO* concept include: a wide field X-ray imaging detector, a high-spectral-resolution imaging X-ray spectrometer (calorimeter), a hard X-ray imaging detector, an X-ray grating spectrometer, high timing resolution spectrometer, and an X-ray polarimeter.

Astrosat

The Indian Space Research Organisation will launch a multi-wavelength astronomical satellite *Astrosat* in mid-2010. It will be placed in a 650-km, near-equatorial orbit. The satellite will carry five astronomy payloads for simultaneous multi-band observations in optical, far ultraviolet, and X-ray wavelengths. The satellite will be used for simultaneous multi-wavelength monitoring of intensity variations in a broad range of cosmic sources; monitoring of the X-ray sky for new transients; sky surveys in the hard X-ray and UV bands; and broadband spectroscopic studies of X-ray binaries, certain clusters of galaxies and stellar coronae.



Astrosat

Gamma-ray observatories

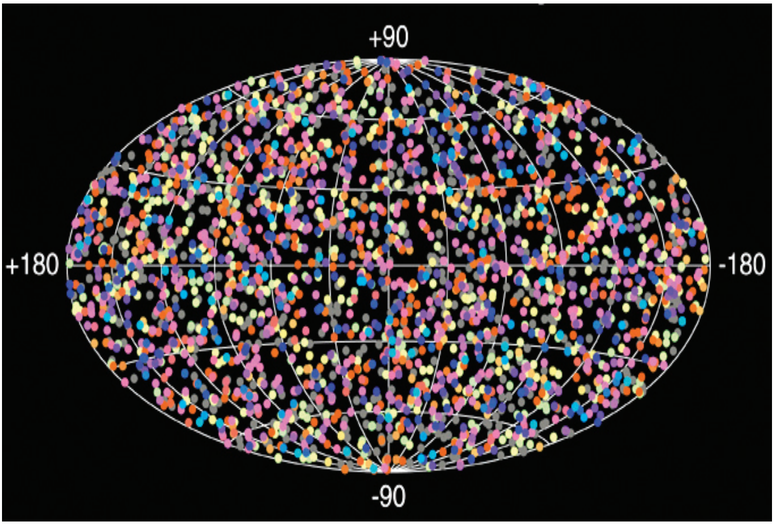
Although gamma rays are a highly penetrating form of radiation, they are readily absorbed in the Earth's thick atmosphere. So, ground based observation is almost impossible, and observations have to be made from space.

The detection of gamma rays from space came about almost accidentally. In the late 1970s the United States had been launching Earth satellites to detect gamma ray emissions from nuclear testing. Surprisingly, these satellites instead discovered bursts of gamma rays coming from deep space. Gamma-ray bursts are brief flashes of gamma-ray energy, lasting from a few milliseconds to a few hundred seconds, which disappear almost as fast as they appear. These bursts occur randomly at a rate of one or two per day. But their source remained a mystery. Several other spacecraft have since been launched to probe gamma rays coming from space.

The first dedicated gamma-ray astronomy mission was *Explorer-XI*. Launched in 1961, it was the first high-energy astrophysics satellite. It detected 22 cosmic gamma ray sources. The *Small Astronomy Satellite* (*SAS*-2) satellite, launched in 1972, discovered a diffuse gamma-ray background. The *COS*-B satellite, launched in 1975, produced the first detailed map of the Universe at gamma-ray wavelengths. The decade of the 1980s saw a few missions, which continued to gather data on gamma-ray burst distributions in the sky and gamma-ray emission from known X-ray sources. More stress, however, was on the development of new technologies, technologies that would be needed to take gamma-ray astronomy to the next level of sensitivity and understanding.

The *Compton Gamma Ray Observatory* (*CGRO*), which was launched in April 1991, carried instruments that were 10 times more sensitive to gamma rays than those on board the earlier gamma-ray satellites. It is named after the American physicist Arthur Holly Compton. By 1999, the *CGRO* had detected more than 2,500 gamma-ray bursts, distributed in a completely random pattern across the sky . But, because of the extremely short duration of the bursts, the *CGRO* was unable to locate their position accurately. In January 1999, *CGRO* for the first time recorded visible light

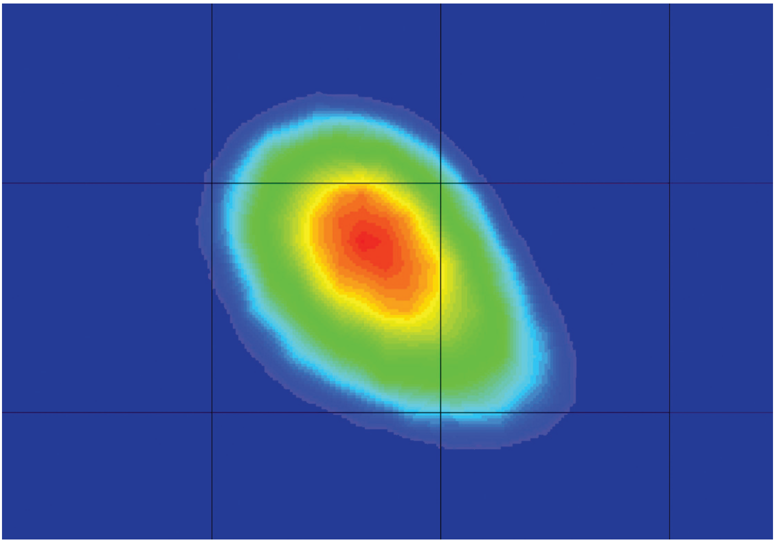
The Compton Gamma Ray Observatory *carried instruments that were ten times more sensitive to gamma rays than those on board the earlier gamma-ray satellites.*



More than 2,500 gamma-ray bursts randomly distributed across the sky, as detected by the Compton Gamma Ray Observatory*.*

emitted at the same time as a gamma-ray burst, a mysterious explosion in the far reaches of the Universe. This particular burst had the power of nearly ten thousand million million (10^{15}) Suns, and the light grew so bright that anyone gazing at the night sky could have seen it using only a pair of binoculars.

During a solar flare in June 1991 *CGRO* recorded gamma rays coming from Sun. The Sun is ordinarily not known to produce gamma rays, but during this solar flare, streams of neutrons poured into the interstellar medium to create gamma rays. The gamma-ray image provided the first evidence that the Sun can accelerate particles for several hours. This phenomenon was not observed before *CGRO* and provided a new understanding of solar flares. *CGRO* re-entered Earth's atmosphere in 2000.



Normally the Sun does not emit gamma rays, but during a solar flare in June 1991 the Compton Gamma Ray Observatory *recorded gamma rays coming from Sun.*

BeppoSAX

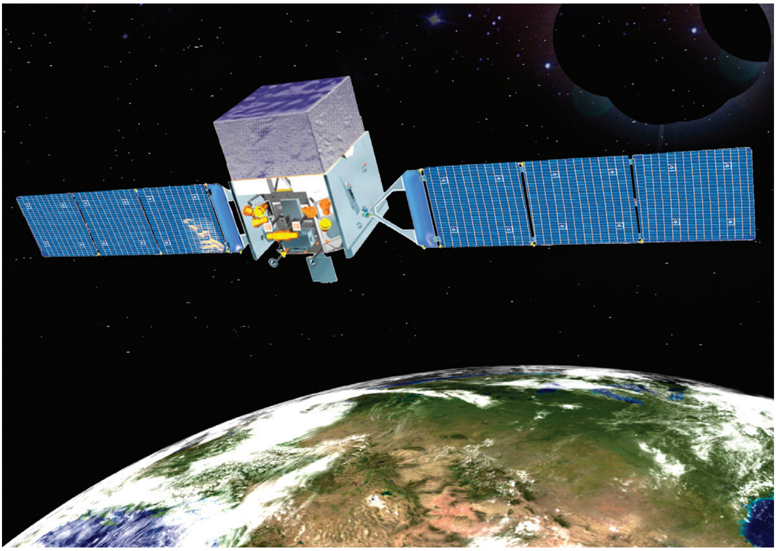
In 1996, an Italian-Dutch gamma-ray observation satellite called *BeppoSAX* was launched into orbit. It was able to achieve a 50-fold increase in positional accuracy; that is, it could locate the source of the gamma-ray bursts much more accurately than the *CGRO* could. In December 1997, *BeppoSAX* detected the most powerful gamma-ray burst till date coming from a source located some 12,000 million light-years away. The powerful burst is believed to have come from the merger of two neutron stars. Theoretical calculations show that in the final seconds of such a merger the brightness of the two stars together can exceed that of a billion galaxies like the Milky Way before they end up in the formation of a black hole.

The *Fermi Gamma-ray Space Telescope*

The newest major space observatory for gamma-ray studies is the *Fermi Gamma-ray Space Telescope* (*FGST*), which was launched into orbit in June 2008. *FGST* is designed to study the most energetic particles of the electromagnetic spectrum, observing physical processes far beyond the capabilities of earthbound laboratories.

FGST's main instrument, the Large Area Telescope (LAT), operates more like a particle detector than a conventional telescope. From within its 1.8-metre cube housing, the LAT uses 80,000 silicon strips to detect high-energy gamma rays with unprecedented resolution and sensitivity, filling in gaps in understanding left by previous missions, and pushing new boundaries in particle physics and astrophysics.

As *FGST* orbits Earth, gamma rays – emanating from jets of plasma streaming from enormous black holes, pulsars,



The Fermi Gamma Ray Space Telescope, *launched in 2008, is designed to study the most energetic particles of the electromagnetic spectrum.*

and other astronomical sources – first encounter several layers of tungsten metal in the LAT. The high-energy gamma rays interact with tungsten's massive atomic nuclei in a way that creates pairs of charged particles: one electron and one positron. These particles are then detected by silicon-strip sensors positioned just below each tungsten layer. Later, these signals are used to reconstruct the direction and arrival time of the original gamma-ray photon. After traversing through the LAT's tracking layers, the particles pass into a caesium iodide imaging calorimeter, where they generate tiny amounts of light – flashes with brightness proportional to the particles' energies.

This multi-step process makes the LAT at least 30 times more sensitive than any previous satellite based gamma-ray detector and allows it to survey the entire sky several times per day. Physicists and astronomers expect that this unprecedented look at the gamma-ray sky will reveal vital information about subatomic particles at energies far greater than those seen in ground-based particle accelerators, about the accelerating powers of supermassive black holes, and about the birth and evolution of the Universe.

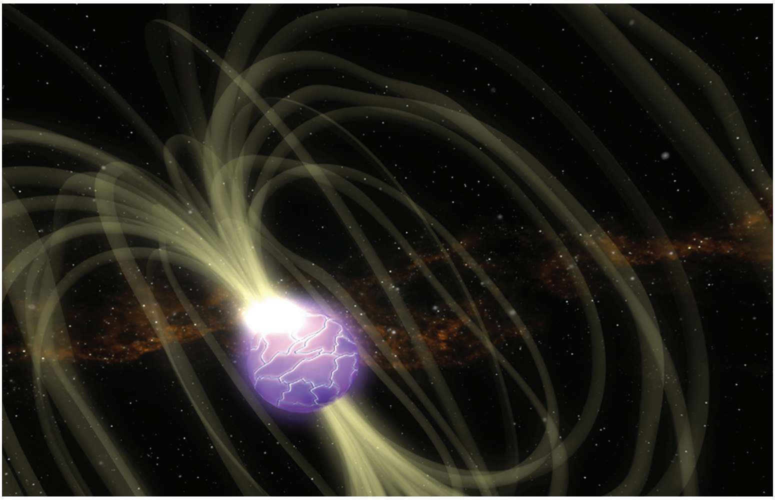
FGST also carries a smaller instrument, called the Gamma-ray Burst Monitor (GBM), to detect gamma-ray bursts and other transient phenomena. Together with the LAT, the GBM enables *FGST* to make gamma-ray burst observations spanning a factor of ten million in energy. A five-year primary mission operating phase has been planned for *FGST*, which may be extended for up to ten years.

In October 2008, *FGST* discovered a pulsar that beams only in gamma rays – the first of its kind. The pulsar, a 10,000-year-old stellar corpse, sweeps a lighthouse-like beam of gamma-rays toward Earth about three times a second emitting 1,000 times the energy of our Sun. Pulsars are neutron stars and are known to emit in radio wavelengths, but never in gamma-ray wavelengths. The gamma-ray-only pulsar lies within a supernova remnant known as 'CTA 1', which is located about 4,600 light-years away in the constellation of Cepheus.

Magnetars

A surprising discovery of gamma-ray observatories has been a rare type of neutron stars known as magnetars, which are the strongest magnets known in the universe. A magnetar is a star with more mass than the Sun, the density of a neutron, and a magnetic field about a thousand trillion (a one followed by 15 zeroes) times stronger than Earth's.

Most neutron stars, which are formed in the violent crucibles of supernova explosions, become pulsars with



Gamma-rays flares from SGR J1550-5418 probably arise when the magnetar's surface suddenly cracks, releasing energy stored within its powerful magnetic field.

relatively weak magnetic fields, spinning and emitting pulses of electromagnetic radiation. Astronomers now believe that some become magnetars, with magnetic fields so intense that the solid neutron star crust buckles and shifts under its influence. The resulting star quakes could repeatedly generate brief flashes of hard X-rays and soft gamma-rays giving rise to the rare but mysterious objects called 'soft gamma repeaters' (SGR), which emit large bursts of gamma rays and X-rays at irregular intervals.

The detection of the most powerful burst of gamma rays from an exploding magnetar named SGR 1806-20 was announced in February 2005. It unleashed about 10,000 trillion trillion trillion (10^{36}) watts of energy. It was 100 times more powerful than any other similar eruption witnessed earlier. Even at a distance of 50,000 light-years, the flare disrupted the Earth's ionosphere. If such a blast happened within 10 light-years of the Earth, it would destroy much of the ozone layer, causing extinctions due to increased radiation.

Thanks to space-borne observatories that can see in infrared, ultraviolet, X-ray and gamma-ray wavelengths, we now have a much broader picture of the Universe. We now understand the extremely violent processes going on in the far reaches of the cosmos. They have made it possible for astronomers to explore distant galaxies and peep into the heart of our Milky Way galaxy. We now know that our Universe is an extremely violent place. If not in the vicinity of our solar system, violent activity goes on almost everywhere in the cosmos where massive stars explode in their death throes with the brilliance of a thousand Suns, or binaries collide, spewing forth deadly gamma rays.

MAGIC

Satellites such as the *Fermi Gamma-Ray Space Telescope* can be used to directly observe high-energy gamma rays up to a few giga-electron volts (Gev = 10^9 electron volts) from space. But satellite-based detectors cannot be used for direct observation of very-high-energy gamma rays (50 GeV and 30 TeV) coming from space (1 TeV = 10^{12} electron volts). However, very-high-energy gamma rays can be observed with a special kind of ground-based telescopes indirectly through the detection of Cherenkov radiation – a kind of radiation created when fast-moving gamma rays pass through matter (in this case, the Earth's atmosphere). Gamma rays kick off a shower of fast-moving particles in the atmosphere, which in turn emit Cherenkov radiation. This process is also responsible for the eerie blue glow of nuclear reactor cores.

The world's largest pair of Cherenkov telescopes called the Major Atmospheric Gamma-ray Imaging Cherenkov Telescopes – MAGIC I and MAGIC II – are now operating at the Roque de los Muchachos Observatory on La Palma,

The Major Atmospheric Gamma-ray Imaging Cherenkov Telescopes (MAGIC I and MAGIC II) are designed to detect Cherenkov radiation produced in the atmosphere by high-energy cosmic gamma rays.

one of the Canary Islands, at about 2,200 m above sea level. It is managed by a collaboration of 17 institutes from Germany, Italy, Spain, Switzerland, Finland, USA, Poland, Bulgaria and Armenia.

The two MAGIC telescopes, each with a diameter of 17 metres and separated by a distance of 85 metres, give the observatory stereoscopic vision, making experiments up to nine times faster and increasing their angular resolution by nearly a third, so that the sources of the gamma rays can be more precisely pinned down. They are designed to detect particle showers released by cosmic gamma-rays, using the Cherenkov radiation, i.e., faint light radiated by the charged particles in the showers as they pass through the atmosphere. Both the telescopes are equipped with photomultiplier tubes of optimal efficiency.

7

The planets close-up

In the early 17th century, the invention of the telescope dramatically changed our views of the planets; instead of mere bright points of light they turned out to be much larger bodies, some with their own moon systems. As telescopes became larger and more powerful, greater surface details and other features of the planets came into view. Some were really fantastic. Jupiter had a large red spot and had several moons in orbit around it; Saturn was surrounded by a majestic ring; Mars had white polar caps that changed with Martian seasons. Between 1781 and 1930 two new planets were discovered beyond Saturn. Our planetary neighbours were turning out to be really fascinating.

But these revelations were nothing compared to what came after space probes began exploring the planets from close quarters. Till date, space probes have been sent to all the planets of our solar system, and they have sent back a wealth of data and fabulous pictures that are once again changing our ideas about the planets. The pockmarked surface of Mercury; cloud-covered Venus; volcanoes, river valleys and gigantic canyons on Mars; turbulent clouds and amazing moons of Jupiter; majestic rings and moons of Saturn; rings of a rolling Uranus; and blue clouds of Neptune were all unknown before space probes caught them from close quarters. The new image of our solar family is turning out to be radically different from what we had known earlier.

One problem with observing the planets from Earth is the large distances that separate us. For example, the planets

Venus and Mars are our nearest planetary neighbours. Even then, when closest to Earth, Venus is more than 40 million kilometres away and Mars is more the 56 million kilometres away. Ground based telescopic observations of the planets Mercury and Venus show almost no details of their surface. Mercury always remains so near the Sun in the sky that for most of the time it remains hidden behind the dazzling glare of the Sun. (Mercury is so elusive that many renowned astronomers including Copernicus have lived out their lives without ever seeing it!) Venus, on the other hand, appears so bright that no details of its surface can be discerned from ground-based observations. The other planets are much, much farther away – Jupiter, 628 million km and Saturn, 1,277 million km. So, even with very powerful ground based telescopes we can see the surface details only up to a point. Atmospheric turbulence and limitations of telescope optics limit the amount of details that can be seen.

Soon after the Space Age dawned, astronomers started thinking of sending space probes to the planets. If we could send space probes with cameras to within a few thousand kilometres of the planets it could show much greater details than can ever be seen from Earth. And this indeed turned out to be so. But sending a spacecraft to a planet millions of kilometres away was not the same thing as placing a satellite in Earth orbit. A spacecraft needs to be carefully guided to keep it on course to its distant destination and that needs not only a fool-proof guidance mechanism but also a reliable two-way communication system.

Navigating in space

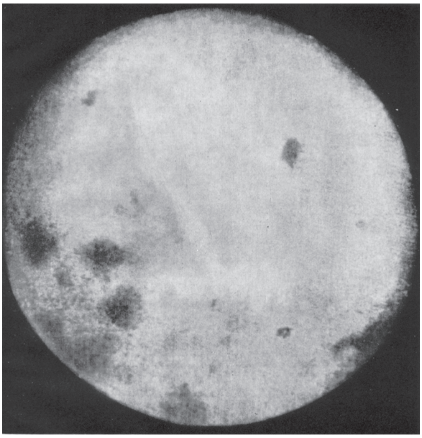
Most interplanetary space vehicles are first launched into a ‘parking’ orbit around Earth. The spacecraft then picks up speed by using Earth’s gravity (and sometimes the gravity of other planets as well) to 'slingshot' it away from Earth and towards its final destination. For guidance *en route* the spacecraft's navigation system uses bright stars as 'markers'. When the vehicle finally arrives at the planet, it does just the opposite and uses the planet's gravity to 'capture' the spacecraft and bring it into orbit around the planet to carry out its assigned tasks.

There are common elements to all spacecraft navigation. All navigation systems use the positions of known objects in space, such as bright stars, as well as the information coming back from the spacecraft to tell where a spacecraft is. Each spacecraft also carries a variety of sensors that help it determine how it is oriented in 3-dimensional space and how fast it is going. There are also a number of ground based tracking systems that help determine that same information. Once the spacecraft's position is known, the flight path is plotted and thrusters are fired to keep it on course. And all the computations of trajectory are done by on-board computers.

Parallel with spacecraft development, advances in imaging, especially digital imaging and remote sensing technology also helped in exploration of the planets. Synthetic aperture radar technology has made possible imaging of planetary surfaces hidden behind cloud layers. Synthetic aperture radar complements photographic and other optical imaging capabilities of a space probe.

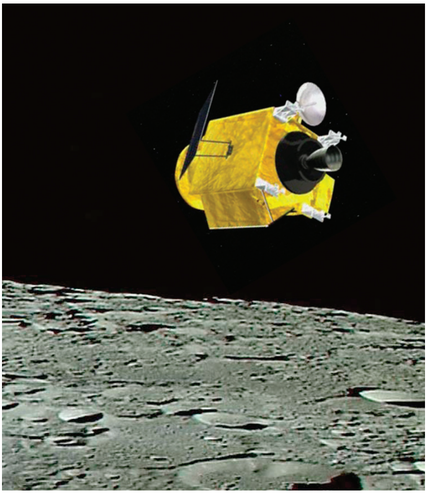
Our nearest neighbour – Moon

We learnt a lot about our nearest celestial neighbour the Moon after space probes were sent to explore it. Space exploration of the Moon began in late 1950's with fly-by, orbiting, landing, and finally human missions. From the



Far side of Moon first photographed by the Soviet Luna-3 *probe in 1959.*

photographs sent back by the probes we got the first glimpse of Moon's far side that always remains hidden from us. In July 1969 the first astronaut landed on the Moon to carry out on-the-spot study of the rocks and soil of Moon. Till 1976, 12 astronauts had set their foot on the Moon and returned to Earth. They brought back almost 400 kilograms of lunar rocks and soil for study. This golden era in lunar exploration – from 1958 to 1976 – not only gave us confidence in our technical capability to do what was earlier considered impossible – to reach the Moon – but also to immensely extend our horizons of space and knowledge.



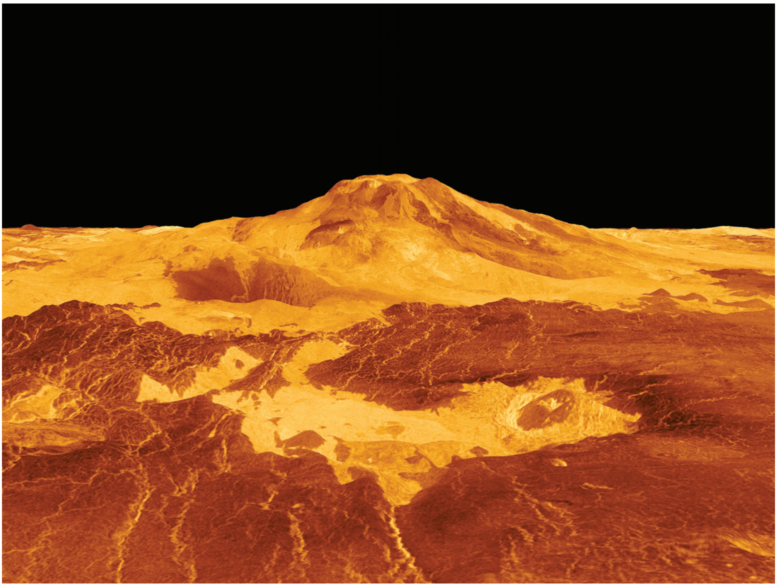
India's Chandrayaan-1 *in Moon orbit.*

Still, despite years of exploration, our nearest celestial neighbour continues to hold many secrets. We still don't know how the Moon came into being. There are many theories, but we don't have any proof to tell us which of them is correct. The structure of the Moon still remains a mystery; we don't know yet what is inside the Moon – whether it has a heavy core like Earth's. The mineral composition of the Moon also remains unclear. We don't know for certain whether the Moon has water – frozen water – under its surface, although there is evidence of water being present in the past. Several new missions including India's *Chandrayaan*-1 are now exploring the Moon to find answers to some of the unanswered questions.

Close encounters

Once it became possible to send spacecraft to distant planets a wealth of data and fabulous images of the planets and their moons became available. The images revealed the true nature of the surfaces of the planets. The surface of Mercury, which was first imaged by *Mariner*-10 in 1973, turned out to be almost like our Moon's – pockmarked with craters, the largest of which is 200 km in diameter, with no atmosphere.

Venus on the other hand was perpetually covered under a thick blanket of cloud; it was impossible to penetrate the cloud layer to see or image what lay below it. Later space missions to Venus, especially Russia's *Venera* lander missions between 1970 and 1981, dropped instrumented capsules and studied the surface beneath its clouds from orbiting spacecraft using radar-mapping technique. Both techniques have brought out startling results. From data sent back by instrumented landers before they were destroyed by the corrosive Venusian atmosphere, the surface of Venus was found to resemble the classical picture of hell, with a surface temperature of a scorching 480°C. Covered with clouds of corrosive sulphuric acid, the Venusian atmosphere is so dense that the surface pressure is of the order of 90 Earth atmospheres. From radar images sent back by the *Magellan* spacecraft, which orbited the planet between August 1990 and October 1994, the surface of Venus has been

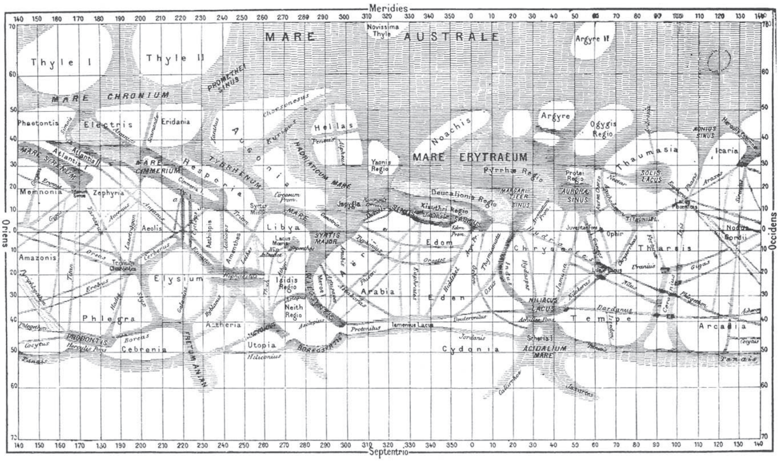


Extinct volcano on Venus imaged by radar on board the Magellan *spacecraft.*

found to be covered with huge impact craters, extinct volcanoes, volcanic craters and solidified lava flows. Many areas of Venus show colossal volcanic features that have been built up by successive overlaying of newer lava flows on older ones.

The Martian enigma

Among the planets of our solar system none has aroused as much public interest and given rise to as many myths as the red planet Mars. For centuries astronomers had marvelled at the fuzzy red ball they saw in their telescope eyepiece and lavished on it their most fanciful dreams – of a planet inhabited by intelligent beings. Interestingly, the myth of intelligent life on Mars arose not out of any scientific discovery but out of just the wrong interpretation of an Italian word. The story goes that, in August 1877, when Mars



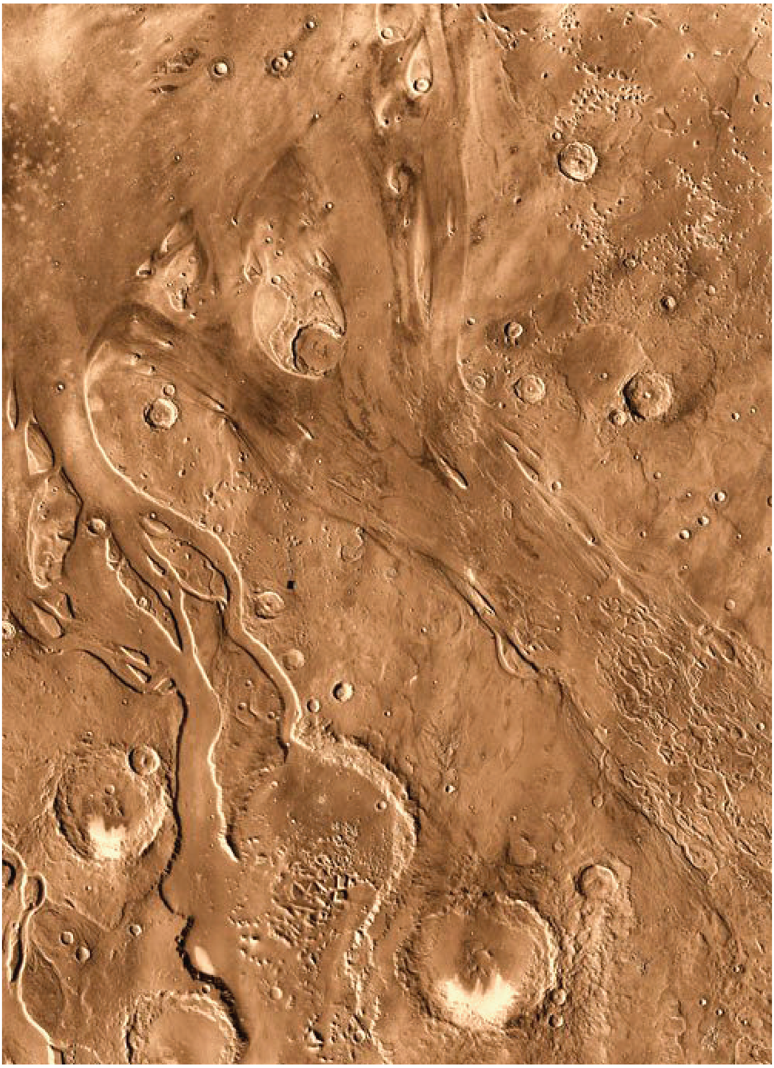
Schiaparelli's map of Mars drawn on the basis of visual observation through telescope.

was closest to Earth, the Italian astronomer Giovanni Schiaparelli was observing the planet with his telescope. During his observations he noted what looked like fine network-like markings on the surface of Mars. He called them *canali*, which in Italian means 'channels'. But later astronomers misinterpreted the word to mean 'canals' – artificial structures meant to carry water for irrigation. In 1894, the famous American astronomer Percival Lowell added a new twist. He suggested that, since the 'canals' on Mars were shaped like straight lines, like man-made canals on Earth, they ought to be the work of intelligent beings. And thus was born the myth of intelligent Martians, which later gave rise to a spate of science fiction stories including H.G. Wells's famous *War of the Worlds*.

Surprisingly, the possibility of the existence of life on Mars was taken quite seriously by astronomers and so, when space technology became available in the 1960s, plans were made to send spacecraft to Mars to make on-the-spot study of any life existing there. But flyby missions to the planet during the 1960s and early 1970s revealed the red planet as a desolate desert, just like Earth's deserts, with no water or vegetation. The photographs sent back during the missions showed vast canyons and massive dead volcanoes larger than any on Earth. The extinct Martian volcano Olympus Mons, which is more than 25-km high and has a crater 80-km in diameter, is the largest volcano in the solar system. But Mars does not have any straight canals; only what appear like dried up, meandering riverbeds. Most important of all, none of the flyby missions could detect any sign of life on the red planet.

In 1976, two *Viking* spacecraft, equipped with instruments to test for signs of life, made soft landing on Mars and carried out chemical tests on Martial soil for biological reactions, but found none. However, the *Viking*s showed the iron-oxide-rich Martian soil to be really red-coloured, which gives the planet its nickname. In July 1997, another spacecraft named *Mars Pathfinder* (renamed *Carl Sagan Memorial Station*), which carried a remote-controlled robot vehicle called *Sojourner*, landed on Mars. Data and pictures sent back by *Mars Pathfinder* startled scientists; the pictures showed extensive flood channels – evidence of copious flows of water on Mars in the distant past. But where all the water has gone no one knows as yet. The only water now remaining on Mars seems to be frozen in its polar caps.

In October 2001 NASA's *Mars Odyssey* went into orbit around Mars to carry out global observations of the planet. The objective was to improve our understanding of the planet's climate and geologic history, including the search for water and evidence of life-sustaining environments. The *Odyssey* mission was designed to analyse the radiation environment to determine its potential effects on human health during future manned missions. Another goal of the mission was to characterise the geology of Mars. The *Odyssey*



Flood channels on Mars photographed by Mars Odyssey.

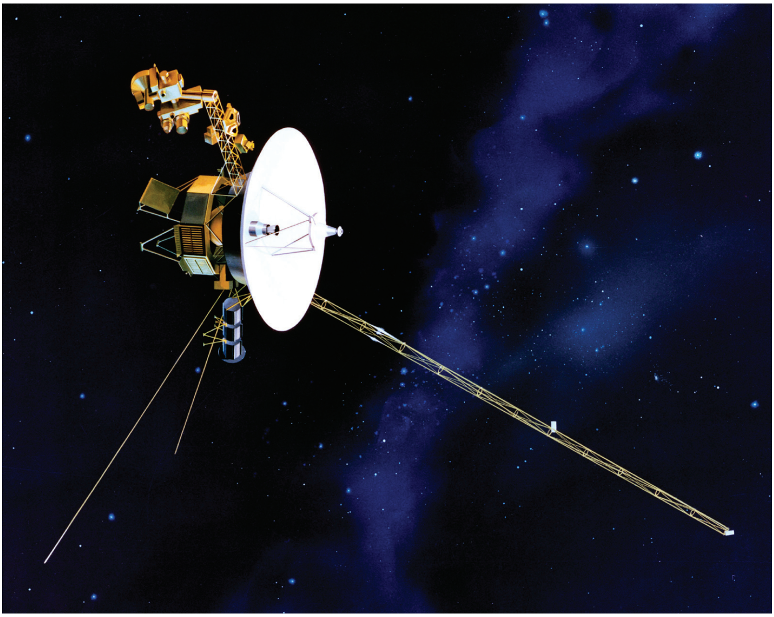
found vast features which look like flood channels, indicating past water flow on Mars. The gamma-ray spectrometer on board the spacecraft has allowed scientists to make maps of the elemental composition of the Martian surface for the elements hydrogen, silicon, iron, potassium, thorium, and chlorine. These and other chemical elements are the building blocks of minerals, minerals are the building blocks of rocks, and all of these relate to the structure and landforms of the Martian surface. An understanding of what Mars is made of, in turn, would provide clues to the geological and climatic history of Mars and the potential for finding past or present life. Finding these elements on Mars means that microbial life could have been (or still be!) present on Mars because they are chemical building blocks for life and its processes. The chemical information gained from *Odyssey* till date provides a base of knowledge that scientists can build upon to determine the likelihood of life on Mars.

In January 2004 two Mars exploration rovers *Spirit* and *Opportunity* were sent to Mars to search for and characterise a wide range of rocks and soils that hold clues to past water activity on Mars. The two spacecraft were targeted to sites on opposite sides of Mars that appear to have been affected by liquid water in the past.

However, although we know much more about Mars today than was known to Schiaparelli, scientists are still debating whether microscopic life forms still survive under the Martian soil. Only future space missions to the planet may settle the issue.

The planetary giants

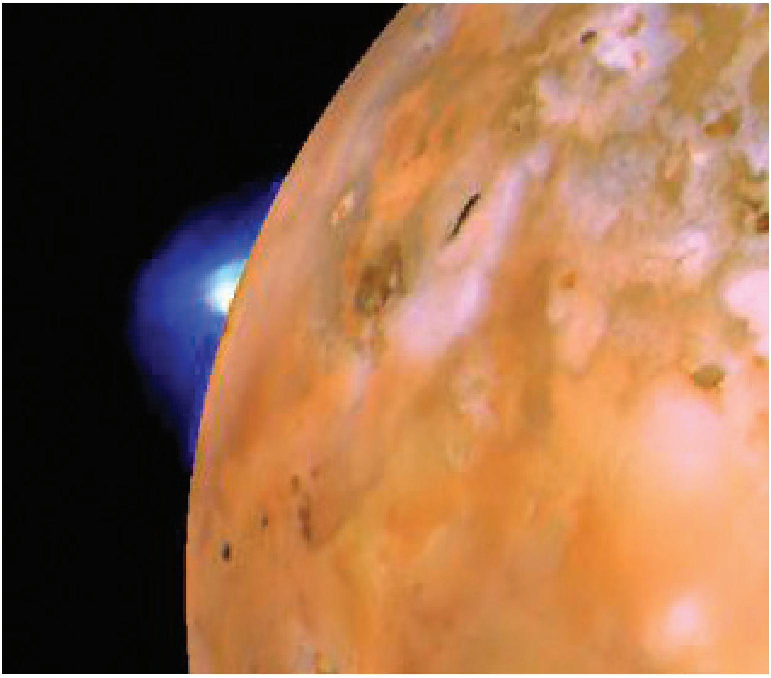
With a diameter of 143,760 km, Jupiter is the largest planet of the solar system followed by Saturn, which has a diameter of 120,420 km. Both the planets make interesting telescopic objects. Even a low-power telescope with a magnification of 50× would show Jupiter as a small disc with two faint dark cloud bands, and its four moons as tiny points of light.



Two Voyager *spacecraft explored four outer planets of the Solar System and sent back fantastic images.*

With larger telescopes a large red spot and a few more of its larger moons can be seen. The view of Saturn is equally fascinating. Although none of its moons is visible through a low-power telescope, its majestic ring system is clearly visible. Before the advent of space probes, only 13 moons of Jupiter and 11 moons of Saturn were known. But the coming of the Space Age has totally changed our views of the two planetary giants.

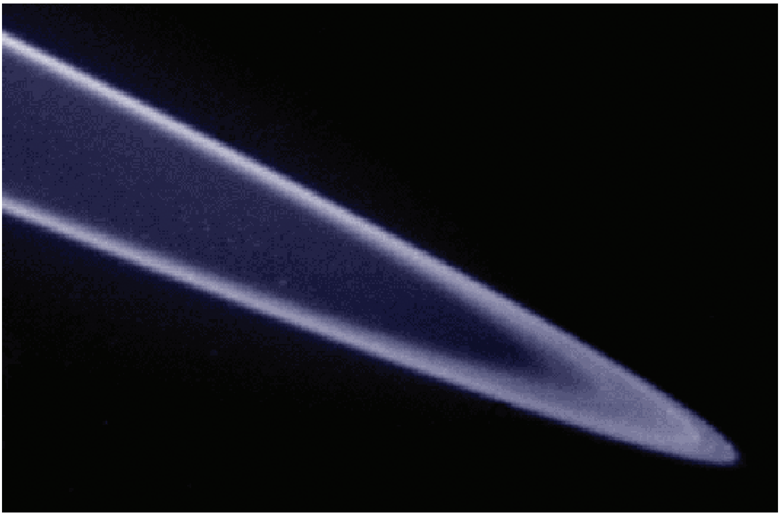
The first spacecraft to fly past Jupiter was *Pioneer*-10, which sent back extraordinary images of the planet and mapped the planet's extensive magnetic field in 1973. But the real surprise came after two *Voyager* spacecraft flew by the planet in 1979. Not only were three new moons discovered, bringing the total number of Jovian moons to 16, but startling differences among Jupiter's four largest



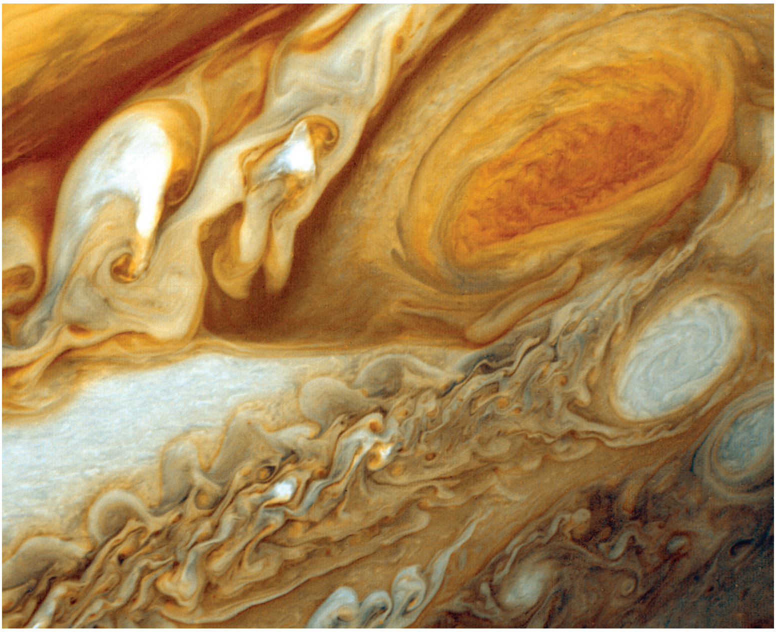
Active volcano on Jupiter's moon Io, photographed by Voyager-2.

moons also came to light. For the first time active volcanoes were discovered outside our Earth – on Jupiter's moon Io, spewing sulphurous vapours 300 kilometres upwards. The surface of Europa was covered with ice, with a 'cracked-egg' appearance. Solar system's largest moon Ganymede was found to be covered with dark cratered areas having lighter grooved terrain, while the surface of Jupiter's second largest moon Callisto was extensively cratered, like our own Moon.

The *Voyager*s also found a thin dust ring around Jupiter, which cannot be seen from Earth even with the most powerful telescopes. From close up, Jupiter's Great Spot was found to be a huge swirling storm cloud that was more than twice our Earth in size. Its red colour was found to be



The Voyagers *also found a thin dust ring around Jupiter, which cannot be seen from Earth even with the most powerful telescopes.*

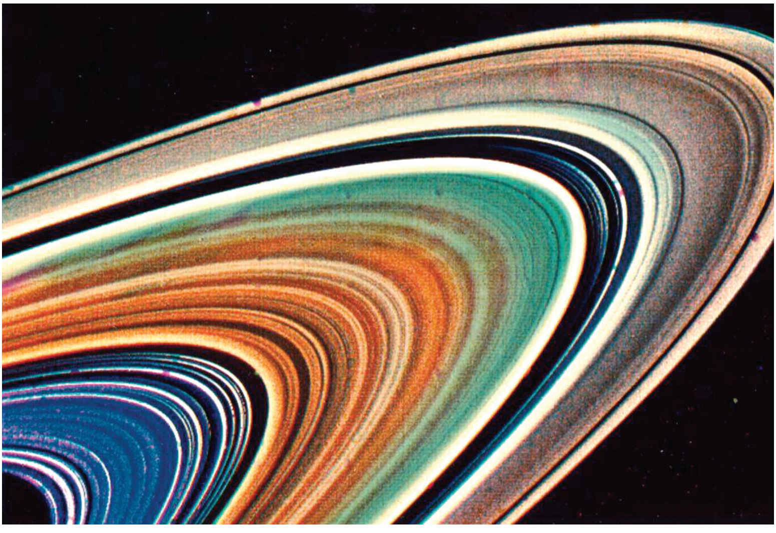


Jupiter's great red spot photographed by Voyager-1*.*

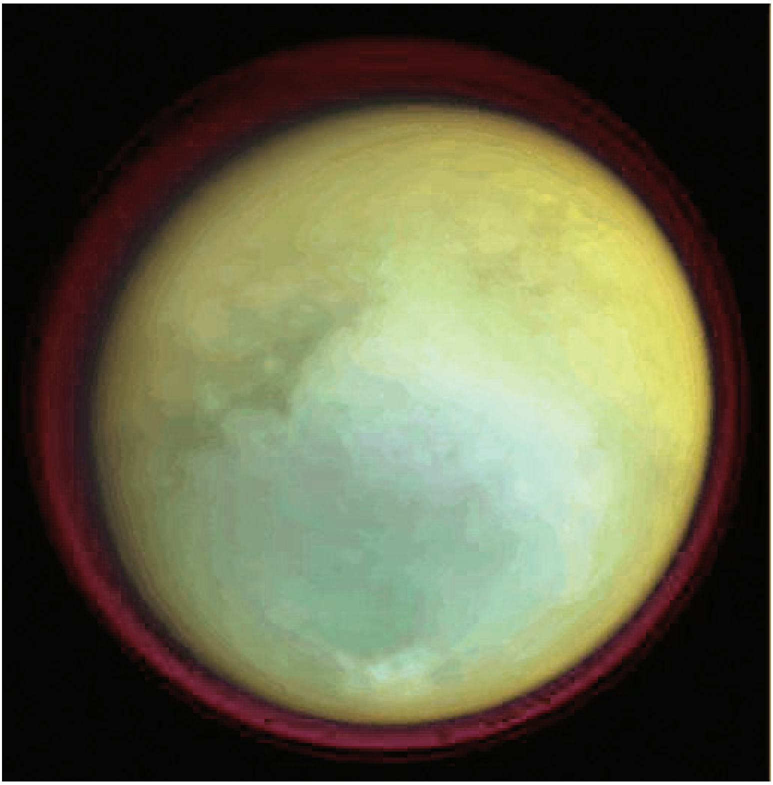
due to the presence of phosphorus compounds. From 1995 to 2003, the *Galileo* spacecraft made observations from repeated elliptical orbits around Jupiter, passing as low as 261 kilometres over the surfaces of the Galilean moons.

After flying by Jupiter both the *Voyager* spacecraft flew on for a rendezvous with Saturn. The *Voyager*s showed details of the ringed planet that are never visible from Earth. The images sent back by the *Voyager*s showed that Saturn's rings are divided into thousands of narrow ringlets that gave it the appearance of a grooved gramophone record. The *Voyager*s also discovered thin rings that appeared to be 'braided' around one another, and as many as seven new moons orbiting the planet, bringing the total number of Saturn's moons to 18.

The *Voyager*s not only discovered several new moons but also sprang a surprise regarding Saturn's largest moon



Detailed structure of Saturn's rings photographed by Voyager-2.



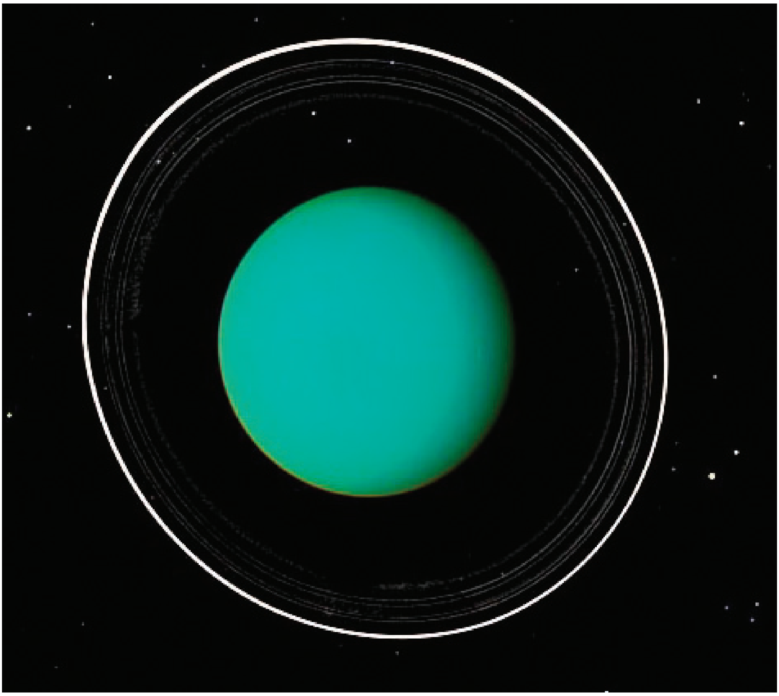
Titan's thick atmosphere photographed by the Voyagers.

Titan. For decades, astronomers had believed Titan (dia. 5,150 km) to be the largest moon in the solar system. But *Voyager*'s data relegated it to second place, just behind Jupiter's moon Ganymede (dia. 5,262 km). The *Voyager*s found Titan to be surrounded by a thick atmosphere, which made it appear larger. Titan's atmosphere is surprisingly dense for so small a moon; at the surface its pressure is twice that of Earth's atmosphere.

Another spacecraft named *Cassini-Huygens* was sent to Saturn to have a closer look at the ringed planet and its largest moon Titan. Launched in 1997, *Cassini-Huygens* went into orbit around Saturn in July 2004. Later, in December 2004, it released the *Huygens* probe – an instrumented capsule – to land on Titan to explore its atmosphere and surface. While descending through Titan's thick atmosphere the *Huygens* probe scrutinised the clouds, atmosphere, and surface of Saturn's largest moon. It was designed to enter and brake in Titan's atmosphere and parachute a fully instrumented robotic laboratory down to the surface. After a two-and-a-half-hour descent the *Huygens* probe landed on solid ground with no liquids in view. However, later radar images showed what appeared to be lakes of liquid hydrocarbon (such as methane and ethane) in Titan's northern latitudes. This was the first discovery of currently-existing lakes anywhere outside Earth. The lakes range in size from about a kilometre to one which is one hundred kilometres across. In March 2007, the Jet Propulsion Laboratory in USA announced that it has found strong evidence of seas of methane and ethane in Titan's northern hemisphere.

Remote worlds

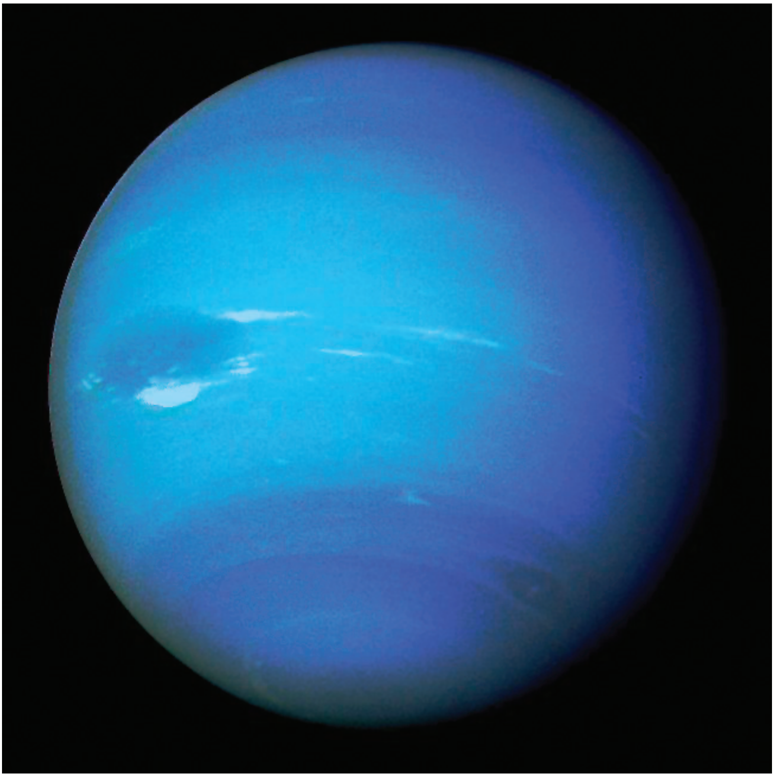
One of the biggest successes of space technology came in January 1986 when the spacecraft *Voyager*-2 swept within 82,000 km of Uranus, the first planet discovered by using modern astronomical tools. Twice as far as from the Sun as Saturn, Uranus turned out to be a planet literally rolling on its side with its south polar region facing the Sun at the time *Voyager*-2 flew by. *Voyager* photographs showed the colour of Uranus to be blue-green, probably due to the presence of methane. From Earth based observations astronomers had known of nine thin rings and five average-sized moons in orbit around Uranus. *Voyager*-2 discovered an additional ring and as many as 10 new moons orbiting the planet near the rings, bringing the total number of known moons of



Uranus and rings photographed by Voyager-2.

Uranus to 15. Close-up views of the large moons showed evidence of recent geologic activity, with the presence of fault canyons, mountains and cliffs.

The next and final destination of *Voyager*-2 was Neptune, which orbits the Sun almost at the edge of the solar system. After flying through space for 12 years, *Voyager*-2 flew by Neptune in August 1989. The encounter yielded several surprises, including what might be the fastest winds and the biggest geysers in the solar system. Winds on Neptune streak westward at a fantastic speed of more than 2,000 km per hour! Neptune was also found to have a 'Great Black Spot' almost resembling Jupiter's Great Red Spot. *Voyager*-2 discovered six previously unknown moons orbiting

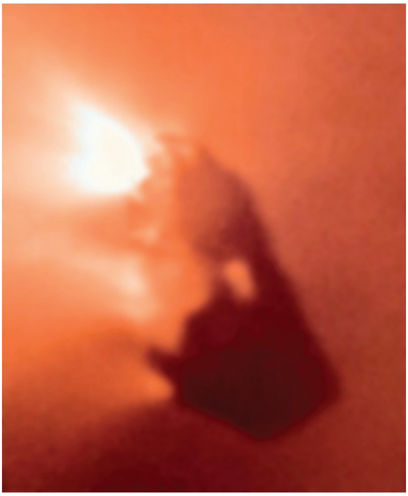


Neptune with great black spot photographed by Voyager-2.

Neptune; only two were earlier known from Earth-based observations. But the most surprising discovery was that of a system of 'fragmented' rings around Neptune, which is unique in the solar system.

Cometary probes

Comets had always been looked at with awe. They appeared suddenly and most sported a long tail. From telescopic and spectroscopic studies it was known that comets basically consisted of a solid nucleus surrounded by a bright gaseous coma and a pair of tails. They were described as 'dirty snowballs'. But it was only in 1986, when Comet Halley made its appearance after a gap of 76 years, that the first close-up study of a comet could be made with a space probe. The European Space Agency's *Giotto* spacecraft approached within 596 kilometres of the nucleus of the comet and sent back the first close-up images of the nucleus. The spacecraft carried 10 instruments including a multicolour camera, and returned data until shortly before closest approach, when the downlink was temporarily lost. *Giotto* was severely damaged by high-speed dust encounters during the flyby and its operation was suspended temporarily.



Comet Halley photographed in 1986 by Giotto *when it approached within 596 kilometres of the nucleus of the comet and sent back the first close-up images of the nucleus.*

The images sent back by *Giotto* showed Halley's nucleus to be a dark peanut-shaped body, blacker than coal, some 15-km long, 7 to 10-km wide. Only 10% of the surface was active, with at least three outgassing jets seen on the sunlit side. Analysis showed the comet formed 4,500 million years ago from volatiles (mainly ice) that had condensed onto interstellar dust particles. It had remained practically unaltered since its formation. *Giotto* found the composition of the material ejected by Halley to be 80% water, 10% carbon monoxide, 2.5% a mix of methane and ammonia, and trace amounts of other hydrocarbons, iron, and sodium.

Deep Impact *probe collides with Comet Tempel-1.*

In January 2005, NASA's *Deep Impact* spacecraft was launched from Cape Canaveral, Florida, USA on a unique mission to Comet Tempel-1. After reaching the comet in July 2005, the spacecraft released an impactor that carved out a large crater on the comet. *Deep Impact* watched the explosion from a safe distance of 500 kilometres, and collected data about the comet's composition. The results were surprising as the material excavated by the impact contained more dust and less ice than had been expected. In addition, the material was finer than expected; scientists compared it to talcum powder rather than sand. Other materials found while studying the impact included clays, carbonates, sodium, and crystalline silicates which were found by studying the spectroscopy of the impact. Clays and carbonates usually require liquid water to form and sodium is rare in space. Observations also revealed that the comet was about 75% empty space. Such data could be gathered only through a space mission.

When Galileo turned his telescope towards Jupiter and Saturn four hundred years ago he saw them to be much more than mere points of light. But that revelation fades before what space technology has been able to achieve. They have revealed the real nature of not only the planets but also of comets. With so much known about the planets and comets, the solar system now looks no stranger than our backyard!

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Tools of Astronomy: How they transformed our view of the Universe

Before the telescope was invented, a host of simple but ingenious instruments were designed and built by astronomers around the world. With the help of these simple tools some of them were able gather enormous amounts of data about the positions and movements of the celestial bodies that contributed immensely to the progress of astronomy. After invention of the telescope in early 17th century and its first use for sky observation by the Italian astronomer Galileo Galilei, the study of astronomy underwent sea change. Larger telescopes and technological advancements in the field of imaging – in optical, infrared, ultraviolet, X-ray and gamma-ray wavelengths – and spectroscopy have revealed a captivating vision of the Universe not known before. This book attempts to take the reader through the fascinating journey of the development and evolution of astronomical instruments through the millennia.

About the author

A retired scientist of the Council of Scientific and Industrial Research, Biman Basu is a former Editor of the popular science monthly Science Reporter. He has been a regular broadcaster over All India Radio for more than 30 years, has scripted several TV documentaries, and published more than 1,000 articles on popular science topics in various publications. He has 27 popular science books to his credit. Some of his books have also been translated into other Indian languages including Assamese, Hindi, Kannada, Marathi, Oriya, Punjabi, Tamil, and Urdu and have gone into multiple reprints. He is a winner of the 1994 NCSTC National Award for Science Popularisation, awarded annually by the Department of Science and Technology.

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